WATER QUALITY ASPECTS OF AN INTERMITTENT STREAM AND BACKWATERS IN AN URBAN NORTH TEXAS WATERSHED: PECAN CREEK, DENTON COUNTY, TEXAS

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Dissertation Prepared for the Degree of

DOCTOR OF PHILOSOPHY (ENVIRONMENTAL SCIENCE)

UNIVERSITY OF NORTH TEXAS

August 2002

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Taylor, Ritchie Don, Water Quality Aspects of an Intermittent Stream and Backwaters in an Urban North Texas Watershed. Doctor of Philosophy (Environmental Science), August 2002, 124 pp., 9 tables, 37 illustrations, references, 48 titles.

Pecan Creek flows southeast through the City of Denton, Texas. Characterized as an urban watershed, the basin covers approximately 63.5 km^2. Pecan Creek is an intermittent stream that receives nonpoint runoff from urban landuses, and the City of Denton's wastewater treatment plant, Pecan Creek Water Reclamation Plant, discharges effluent to the stream. Downstream from the City of Denton and the wastewater treatment plant, Pecan Creek flows about 6,000 m through agricultural, pasture, and forested landscapes into Copas Cove of Lake Lewisville, creating backwater conditions. Pecan Creek water quality and chemistry were monitored from August 1997 to October 2001. Water quality was influenced by seasonal, spatial, climatic, and diurnal dynamics. Wastewater effluent discharged from the Pecan Creek Water Reclamation Plant had the greatest influence on water quality of the stream and backwaters. Water quality monitoring of Pecan Creek demonstrated that dissolved oxygen standards for the protection of aquatic life were being achieved. Water quality modeling of Pecan Creek was completed to assess future increases in effluent flow from the Pecan Creek Water Reclamation Plant. Water quality modeling indicated that dissolved oxygen standards would not be achieved at the future effluent flow of 21 MGD and at NPDES permitted loadings. Model results with application of a safety factor indicated that the maximum allowable concentrations for a 21 MGD discharge would be 2.3 mg/L of ammonia and 7.0 mg/L of biochemical oxygen demand at summer conditions. Drought conditions that

occurred from 1998 to 2001 reduced water levels in Lake Lewisville and impacted dissolved oxygen water quality in Pecan Creek. Water quality observations made during the period of drought allowed for the development of a model to estimate the zone of the dissolved oxygen sag in Pecan Creek based on reservoir elevation. Finally, monitoring results were analyzed with nonparametric statistical procedures to detect water quality changes in the backwater area of Pecan Creek, as influenced by storm events.

ACKNOWLEDGMENTS

Project financial support was provided under the Clean Rivers Program, as administered by the Trinity River Authority (TRA), in cooperation with the Texas Natural Resource Conservation Commission (TNRCC) and by the City of Denton, Texas. The City of Denton Environmental Laboratory provided water chemistry analyses for the study from 1997 through 2000.

This project was associated with the University of North Texas, Institute of Applied Sciences, Environmental Science Program. A special thanks goes to my committee, Drs. Dickson, Acevedo, Atkinson, Kennedy, and Waller. I appreciate the assistance and insights provided by Vanneta Verbosh and Jim Coulter with the City of Denton. Thanks to Gerald Maschmann for his help in collecting field data and samples from 1997 through 1998. I would also like to thank Kenneth Banks and Margaret Forbes for their support through the process. Lastly, but not least, I am indebted to my wife, Juliana, and my children Everett and Deanna. They were a constant source of encouragement, love, and inspiration.

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CHAPTER 1

INTRODUCTION

Research presented in the following manuscripts comes from a water quality study conducted on Pecan Creek and its backwaters in Lake Lewisville, in Denton County Texas. All research presented herein was funded by the City of Denton, through the Clean Rivers program as administered through the Trinity River Authority for the Texas Natural Resources Conservation Commission. The study of Pecan Creek began in July of 1997 and ended in October of 2000. The primary purposes of the Pecan Creek water quality study were to collect a baseline of water quality to assess the stream condition, develop data sets that could be used to model the wasteload from the City of Denton's Pecan Creek Water Reclamation Plant (PCWRP), and provide data that could be used to evaluate future wasteload changes in the watershed. Components of the overall study also included the collection of physical, chemical, and biological data for Pecan Creek. Objectives of my specific research are 1) to determine the water quality impacts of the City of Denton's PCWRP, 2) assess the temporal and spatial trends of dissolved oxygen in the Pecan Creek system, 3) determine the influence of a three year drought on the water quality conditions of Pecan Creek and the implications for future monitoring, and, 4) examine the influence of storm events on the water quality of the backwater areas of Pecan Creek.

The first manuscript develops a wasteload allocation for the PCWRP. This manuscript describes the current water quality conditions of Pecan Creek. Although data were collected in 1997, 1998, 1999, and 2000, only data collected in the summer months of 1997 and 1998 were used to develop model sets for the U.S. EPA QUAL2E water quality model. Data collected during 1997 and 1998 represented critical conditions when Lake Lewisville was at normal pool elevation and backwaters were present. Under those conditions the lotic length of Pecan Creek is reduced to a minimum and the wasteload from the PCWRP is exerted at a distance of approximately 5,134 m downstream from the discharge. Under drought conditions, as experienced in 1998, 1999, and 2000, the wasteload of Pecan Creek is displaced further downstream and has more spatial distance to degrade prior to contacting reservoir backwaters. Objectives of this manuscript were to develop a wasteload allocation for the PCWRP, project future loading scenarios, and describe the National Pollutant Discharge Elimination System limits that would be necessary to protect the dissolved oxygen resources of the stream as an increased effluent flow of 21 MGD.

The second manuscript provides a more detailed analysis of the dissolved oxygen resources of Pecan Creek. Data were analyzed for both temporal and spatial trends. This paper evaluates the water quality conditions in an intermittent urban stream in North Texas that receives a municipal wastewater effluent. Results are presented that illustrate the water quality changes that can occur when such a stream becomes effluent dominated. Pecan Creek also provides a unique example of the water quality characteristics of an intermittent stream in an urban watershed that flows into the backwaters of a drinking water and recreational reservoir, Lake Lewisville.

Third, in the series of manuscripts, is a paper that describes the changes in dissolved oxygen resources that occurred in the Pecan Creek backwaters, as influenced by the drought that began in 1998 and ended in 2000. This manuscript provides information specific to the influence of Lake Lewisville water levels on Pecan Creek water quality. Implications of this study are that changes should be made in the way NPDES permits are established in Texas and variable compliance points should be established for streams that enter reservoirs when assessing water quality standard attainment. Specific methods are applied that can be used on effluent dominated intermittent streams throughout Texas.

Finally, the fourth manuscript provides a case study of the impacts of storm events on the water quality of Pecan Creek. This manuscript is especially important for environmental managers that conduct water quality monitoring and modeling to support NPDES permit conditions. Information presented provides an approach to detecting the duration of stormwater effects and identifying data sets that are under the influence of these conditions. The approach applied provides researchers with methods that can assist in selecting water quality data sets that can be used to accurately monitor and model impacts from point source discharges.

As a complete set, the manuscripts provide a detailed assessment of the water quality conditions of Pecan Creek, with a focus on the dissolved oxygen resources. Future research conducted in the basin can be assessed against this body of work and environmental management of the watershed should utilize the information presented.

CHAPTER 2

WASTELOAD ALLOCATION FOR AN URBAN INTERMITTENT STREAM RECEIVING A MUNICIPAL WASTEWATER EFFLUENT: PECAN CREEK, DENTON COUNTY TEXAS

Introduction

Wasteload allocations (WLA) are used to determine the allowable waste loads from point source dischargers for compliance with water quality standards. Procedures for WLAs require that the relationship between pollutant loads and the resulting responses of the water body be investigated. A standard procedure is to apply a mathematical model to assist in the determination of cause-effect relationships in natural water systems (Thomann and Mueller 1987; USEPA 1991; Cleveland 1991; Park and Uchrin 1996). WLA methods have been developed for streams, rivers, lakes, and impoundments (Driscoll, Mancini, and Mangarella 1983; Leopold 1949; Gilbert 1987). Methods for WLAs have been documented for alternative scenarios as well, such as fish farm wastes and a macrophyte growing impoundment system (Kelly, J. Stellwagen, and A. Bergheim 1996; Park and Uchrin 1996). Research has been conducted to address the risks of WLA modeling and impacts of water quality modeling uncertainty on environmental management (Warwick and Roberts 1992; Korfmacher 1998). Additionally, WLAs are used as part of the total maximum daily load (TMDL) process to define the impacts of point sources of pollution (USEPA 1999).

Streams in arid to semi-arid regions of the United States may have seasonal periods of extremely low or no flow, and effluent discharges to these streams can comprise a majority of the stream flow (Atkinson et al. 1997). In particular, many intermittent streams in North Central Texas enter reservoirs and create backwater areas that have unique water quality characteristics. Therefore, developing WLAs for these intermittent streams is critical for the maintenance of dissolved oxygen (DO) standards for the protection of aquatic life and offers challenges in permitting, compliance, water quality modeling, and WLA development.

The City of Denton, in Denton County Texas (Figure 2.1), has placed great importance on environmental management and is concerned with the water quality of Pecan Creek and the environmental services the stream provides (City of Denton. 1999b). Namely, the stream and its associated backwaters have the ability to assimilate a waste load from the City, both point and nonpoint sources (Atkinson et al. 1997). This is but one of the values of Pecan Creek and with rapid urbanization waste assimilation could be reduced (Thomann and Mueller 1987) and environmental health could be altered (Karr 1991; Karr 1999; Norris and Thoms 1999). As the population of Denton grows and is projected to double by 2018 additional wastewater treatment services will be needed (Coulter 1999; City of Denton 1999). Statistics and projections indicate that Denton will increase from a population of about 74,000 in 1999 to 150,000 by 2018. Specifically, the City of Denton needs to expand wastewater treatment services at the current Water Reclamation Plant (WRP), Pecan Creek Water Reclamation Plant (PCWRP), shown in Figure 2.2. Expansion of the PCWRP will allow for increased capacity to meet the water quality standards for Pecan Creek and the associated backwaters in Lake Lewisville. Thus, it is a major priority for Denton to develop a WLA for the PCWRP point source discharge to Pecan Creek that flows into the backwaters of Lake Lewisville.

This WLA study was conducted in order to determine the current water quality characteristics, assess the impact of a WRP discharge on Pecan Creek water quality during critical summer low-flow and high temperature scenarios, and project PCWRP loadings of 5-day biochemical oxygen demand (BOD_5) and ammonia (NH_3-N) that will attain DO standards at future effluent discharge flows. This research provides a unique case study of an effluent dominated intermittent stream entering a backwater area of a reservoir and assesses the application of the Enhanced Stream Water Quality Model, QUAL2E, under these conditions.

The occurrence of point and nonpoint sources entering intermittent streams is common in Texas, yet relatively few water quality studies exist that demonstrate characteristics of these streams and WLA development. Likewise, a method was developed for relating model projected water column average DO values to epilimnion average conditions that are specified in the Texas water quality standards.

Methods

Beginning in June of 1997 research was initiated to determine the water quality characteristics of Pecan Creek, Denton County, Texas. Study methods were designed to evaluate the influence of the PCWRP discharge on downstream DO resources and collect data that were adequate to develop a water quality model set for WLA projections.

Study Area

Pecan Creek is located in Denton County, Texas. Comprising a watershed of approximately 24.57 square miles, land use was about 75% urban, including vacated lots. Pecan Creek drains most of the City of Denton and eventually flows into Lake Lewisville as shown in Figure 2.1. Lake Lewisville serves as a drinking water supply reservoir for the cities of Denton, Dallas, and Lewisville, and provides recreational and flood control benefits.

Water quality monitoring and modeling efforts on Pecan Creek began in the summer of 1997. A study of Pecan Creek was initiated in response to the Texas Natural Resources Conservation Commission (TNRCC) review of the PCWRP's National Pollutant Discharge Elimination System (NPDES) permit renewal application. The application was submitted for the PCWRP discharge to Pecan Creek, a discharge with permit limits for effluent flow, BOD_5, and NH_3-N. Discharge limits for these parameters are to provide for the attainment of specific waterbody uses. Pursuant to water quality regulation §307.7, Site-Specific Uses and Criteria, DO must be maintained within specific limits for the lotic reaches of Pecan Creek and within the lentic backwater reaches, considered to be part of Lake Lewisville (TNRCC 1997; TNRCC 1999). As part of the NPDES permit evaluation process, TNRCC applied an uncalibrated water quality model, QUAL-TX, to the PCWRP permitted loadings of BOD_5 and NH_3-N. Water quality modeling was done to assess DO (mg/L) attainment in Pecan Creek. Initial modeling efforts concluded that water quality standards for DO, in the backwater areas of Pecan Creek, would be violated under the NPDES permitted loadings (10 mg/L BOD_5, 3 mg/L NH_3-N and 4 mg/L DO at 15 MGD effluent flow). Model results showed that even if the wasteload was 5 mg/L BOD, 2 mg/L NH_3-N, and 6 mg/L DO, at an effluent flow of 15 MGD, water quality standards would be violated. TNRCC's modeling conclusion was that the facility could not discharge effluent at the current permitted loadings without causing DO concentrations, in the impounded portion of Pecan Creek, to drop below the 5.0 mg/L DO standard for Lake Lewisville. Results implied that the discharge permit might not be renewed without modification or upgrades to PCWRP (Taylor et al. 1999; Coulter 1999).

Following discussions with TNRCC, a water quality study of Pecan Creek was initiated to collect data during critical summer low-flow. The study was designed to collect data to calibrate an appropriate water quality model for Pecan Creek and to develop a WLA for the PCWRP's effluent discharge to Pecan Creek, at current and future loading scenarios. Likewise, such a model could be used to assess WRP upgrades, loadings that will occur during elevated storm water flow, varied seasonal conditions, and to evaluate nonpoint source loadings.

Water Quality Monitoring

Based on stream characteristics, eleven sampling stations were established: one upstream from the facility, one at the wastewater discharge, three stations in the free flowing reaches, two stations at the stream reservoir interface, and four stations in the receiving cove of Lake Lewisville (Figure 2.2). Water quality surveys were conducted from July through September of 1997 and in the summer of 1998. A total of ten surveys were completed that included the measurement of dissolved oxygen (DO), pH, specific conductance, temperature, and total dissolved solids. Monitoring was a critical component, as historical data was limited and information on water quality characteristics of effluent dominated, intermittent urban streams, which contact backwater areas of reservoirs, was not available.

Each sampling event was conducted over an approximate 24-hour period. Water quality at each station was collected at up to four times over a 24-hour period. Sampling consisted of taking measurements in a dawn to dusk pattern to establish the diurnal fluctuations in the parameters at each location. In this manner, average DO conditions could be assessed for water quality standard attainment (TNRCC 1999).

Water quality data were collected with a Hydrolab® Datasonde and Suveryor 4, water quality meter. The methodology for collecting samples varied between the upstream and downstream reaches, as conditions were distinct. All samples collected in the upstream reaches were taken just below the water surface or about 0.3 m below the surface. Sampling in backwater and reservoir zones, with increased depths, required that sampling be conducted throughout the water column at mid-channel and in 0.5 m increments at a location. For example, to sample at a station the water quality meter would be lowered to the bottom and the total depth (m) would be recorded. The meter would then be raised to the closest 0.5-m increment above the bottom and measurements taken. Sampling would then continue at each 0.5-m increment until a depth of 0.5 m below the surface was attained. Measurements were also made at a depth of 0.3 m below the surface in accordance with TNRCC monitoring methods.

Water quality surveys were conducted to assess the temporal and spatial dynamics, to determine compliance with applicable water quality standards, primarily DO, and to assess the diurnal variability. Table 2.1 shows the water quality criteria for Pecan Creek (TNRCC 1997). According to the WRP NPDES permit, TNRCC applies DO water quality standards for Pecan Creek above and below a Lake elevation of 522 feet above mean sea level, which is the summer conservation pool elevation. Therefore, according to TNRCC, Pecan Creek upstream from the 522 feet elevation is considered the advective portion and below is considered the impounded section of Pecan Creek or the Pecan Creek Arm of Lake Lewisville.

Table 2.1 Pecan Creek DO Standards

Waterbody - Aquatic Life Use Sub-Category	DO Criteria Mean/Min (mg/L)	DO Criteria in Spring Mean/Min (1) (mg/L)
Pecan Creek Arm of Lake Lewisville – High	5.0/3.0	5.5/4.5
Pecan Creek - Limited	3.0/2.0	4.0/3.0

(1) Spring criteria to protect fish spawning periods are applied during that portion of the first half of the year when water temperatures are 63.0F to 73.0F.

Water Chemistry Monitoring

Water Chemistry parameters monitored related to assessing the impact of the WRP discharge on DO levels in the lotic and lentic portions of Pecan Creek for development of a WLA. Surface grab samples for laboratory analyses were collected at 231 m upstream from the effluent discharge, from the effluent prior to discharge, and at 1,762 m, 5,134 m, 5900 m, and 6,400 m downstream from the effluent discharge. All samples were collected from the main body of flow in lotic areas or at mid-channel in the lentic areas of Pecan Creek.

Water chemistry parameters included Chlorophyll *a*, 5-day Biochemical Oxygen Demand (BOD_5), Ammonia (NH_3), Nitrate-Nitrite ($NO_3 + NO_2$), Dissolved Ortho Phosphorous (DOP), Total Phosphorous (TP), Total Kedjhal Nitrogen (TKN), Total Organic Carbon (TOC), Total Suspended Solids (TSS), and Volatile Suspended Solids (VSS). Water chemistry samples were analyzed by the City of Denton Municipal Laboratory, with the exception of Chlorophyll *a*, according to routine methods (American Public Health Association, American Water Works Association, and Water Environment

Federation 1992; USEPA 1983). Chlorophyll *a* samples were analyzed in the University of North Texas Limnology Laboratory with a Turner Designs 10-AU fluorometer by prescribed methods (Turner Designs 1994; Welschmeyer 1994; Arar and Collins 1992).

Physical Stream Characterization

Measurements of stream morphology, velocity, and flow were completed for Pecan Creek. In 1997 a series of flow measurements were made throughout Pecan Creek to provide a physical characterization for water quality model development. Permitted PCWRP flows are based upon metered flow from the facility. Due to the permitting of WRP loadings to Pecan Creek based on measured plant flow, PCWRP flow plus a measured background flow was used to attain total instream flows for Pecan Creek. Additionally, background flows were impacted by effluent discharged by the City of Denton's Municipal Power Plant through the sampling period of 1997 and 1998. The Power Plant flow was monitored and reported according to monthly NPDES requirements.

Methods for stream width, depth, velocity, and flow measurement were in accordance with standard stream gauging methods (Buchanan and Somers 1965). To make a flow measurement, a stream transect would be divided into evenly spaced segments, as depth and width of the stream would allow. Within each segment a center point was established at which depth and velocity measurements were made. Velocity measurements were made at 0.6 of total depth at each center point. Center point velocity (m/s), depth (m), and width (m) of each measurement segment were used to calculate flow for each segment.

Calculated transect widths were used to estimate velocities for each reach in the Pecan Creek model. In this way a representative average velocity by reach could be determined for the model. Additionally, dye studies were conducted to further assess the time of travel through the lotic stream segments (Kilpatrick and Wilson 1988). Physical measurements allowed for quantification of the distinct physical zones for incorporation into the QUAL2E water quality model (Brown and Barnwell 1987).

Water Quality Modeling

An approach to water quality modeling was determined based on the characteristics of Pecan Creek, the regulatory requirements, future modeling needs, and an accurate model of Pecan Creek DO characteristics. As such, the applicability of the QUAL2E enhanced stream water quality model was tested (Brown and Barnwell 1987). QUAL2E was chosen as it is similar to the QUALTX model, typically utilized by TNRCC for stream WLA determinations in Texas, has a user friendly Windows® interface (USEPA 1995), unlike QUALTX, and is widely accepted for stream modeling applications. It was first hypothesized that the QUAL2E model would not be robust as to allow modeling of backwater areas, therefore, a method had to be developed to relate water column average DO, which was modeled, to epilimnion DO concentrations for water quality standard attainment (TNRCC 1999; TNRCC 1997). In this manner, the QUAL2E model was applied in an empirical format, utilizing field data to adjust modeling results to standard attainment conditions.

Modeling of Pecan Creek was accomplished by dividing the stream system into distinct reaches based on physical characterization. The QUAL2E model was applied to all stream reaches including the backwater areas of Pecan Creek and those reaches impounded by Lake Lewisville. The primary focus of modeling was to accurately model water column average DO throughout the stream system.

Assessment of DO standard attainment in backwater areas that exhibited temperature stratification was dependent upon the epilimnion DO, according to TNRCC water quality regulations. Although QUAL2E can be used in a dynamic manner to address diurnal oxygen changes and potentially model epilimnion DO (Brown and Barnwell 1987), an empirical method was chosen. We wanted to assess an empirical method that could be readily applied to effluent dominated intermittent streams without the need for sophisticated dynamic modeling. Preliminary results indicated that the QUAL2E model could be used to model water column average DO conditions in the backwaters. Therefore, an empirical method was needed to relate water column average DO to epilimnion average DO.

Model calibration was accomplished by developing a model data set based on measured stream conditions, selecting rates and coefficients based on literature values and professional judgment, and by adjusting uncertain parameters within accepted limits to obtain a good fit to observed DO conditions. The July 31, 1997 water quality data set was used for calibration. Afterwards, data collected from August 1997 through June of 1998 were used for model evaluation. Model evaluation was the process of determining the uncertainty of the model for predicting observed DO conditions. Evaluation provided for an assessment of model error and produced data to ascertain the need for a safety factor. The safety factor would be used to reduce the potential model error and protect the DO resources of Pecan Creek. Finally, sensitivity analysis was conducted to determine the model parameters that had the greatest influence on DO results.

Waste Load Allocation

The calibrated and evaluated QUAL2E model set was used to project DO in Pecan Creek at current NPDES permitted loadings and at future projected loadings, based on PCWRP facility upgrades. Projections were made for critical summer low-flow conditions as determined from reference stream temperature evaluation and assessment of measured Pecan Creek flow. Upgrades to PCWRP have been planned to improve capacity to treat wastewater from the growing population of the City of Denton. Capacity improvements are planned to increase the current effluent discharge of 15 MGD to 21 MGD. Model results were used to develop predictive equations that could be used to assess various BOD_5 loading scenarios at current and future conditions. The method used involved plotting results of model runs for various loadings and fitting a predictive equation to the model generated data. Utilization of model results in this manner provided a direct methodology for WLA determinations. Application of the predictive equations allowed the WRP flow to be related to BOD_5 and NH_3-N loadings, and thus project acceptable NPDES permit concentrations.

Results

Water quality, water chemistry, physical stream assessment, water quality modeling, and WLA projections encompassed the results for this study. As stated previously, results were utilized to assess the influence of the PCWRP on DO resources of Pecan Creek and Lake Lewisville, develop a WLA for PCWRP, and develop methods for WLA determinations for DO in backwater regions of a North Texas reservoir.

Additionally, results addressed the use of the QUAL2E stream water quality model on an effluent dominated intermittent stream that enters a backwater area of a reservoir. This research provided a case study of such a scenario in the semi-arid Southwest of the United States, specifically North Central Texas.

Water Quality

Data collected in 1997 could be characterized as being taken during critical backwater conditions or when the 522 feet Lake Lewisville pool elevation criterion was met. After June of 1998, drought conditions in North Central Texas caused the Lake Lewisville pool elevation to recede. For water quality modeling to develop NPDES permit conditions, the summer 1997 water quality data were chosen for analysis, as these data met the TNRCC criterion for the critical condition of an impounded Pecan Creek.

Water quality data collected from Pecan Creek on July 31 through August 1, were used to calibrate and evaluate the QUAL2E model. Data that were under the influence of stormwater runoff were not used in model calibration or evaluation. Specifically, DO and temperature were the most critical parameters collected. During the summer of 1997, DO concentrations (mg/L) in the impounded portions of Pecan Creek, thus Lake Lewisville, exhibited a wide variability. Exploratory data analysis indicated that DO values in the lotic reaches were normally distributed as opposed to non-normally distributed DO values for lentic reaches. These results were confirmed by testing for goodness of fit with the Shapiro-Wilk test (Shapiro and Francia 1972). A typical pattern for Pecan Creek DO (mg/L) was reduced variability in the lotic reaches with a slight increase due to the effluent and highly variable conditions in the backwater reaches. For example, the DO profile for July 31, 1997 shows DO conditions to be between 5.0 mg/L and 8.5 mg/L for the background (-231 m) and lotic stations (+643 m, +1762 m) in comparison to a highly variable transition and backwater zone, +3,900 m to +6,856 m downstream from PCWRP. A summary of DO (mg/L) concentrations, for all monitoring sites in 1997, is presented in Table 2.2 and Figure 2.3. DO concentrations ranged from 2.77 to 7.60 mg/L at the background (upstream) station (-231 m), 5.66 to 8.26 mg/L just downstream from the discharge (+643 m), 4.45 to 20.0 mg/L in the backwater slough (+4,300 m), and 3.68 to 17.32 in the cove (+6,400 m), for comparison. Standard deviations for these data showed increased variation with distance downstream. Locations within the area of Pecan Creek's interface with Lake Lewisville showed the greatest variability (+4,300 m and +5,134 m) in DO concentrations. The boxplot in Figure 2.4 indicates the presence of outliers for the sites from 4,300 m to 6856 m downstream from the discharge.

Monitoring of Pecan Creek water quality indicated that mean DO increased following input of the PCWRP effluent and then would decrease to a distance of about 3,900 m downstream, as shown in Figure 2.3. Results show that the critical point for assessment of the BOD_5 and NH_3-N wastewater loads from PCWRP occurred at a distance of about 3,900 m to 5,134 m downstream. With an increase in algae productivity, as indicated by chlorophyll *a* measurements (Figure 2.5), DO increased from 4,000 m to 7,000 m downstream. Increases in DO concentrations were variable with time and distance due to fluctuations in reservoir surface levels, effluent flow, and effluent loads of BOD_5, NH_3-N, and nutrients.

Several critical parameters for DO standard attainment are the minimum DO and duration, average DO (lotic reaches), and surface or epilimnion average DO (lentic reaches). The standard classification of a discontinuous water surface layer, epilimnion, is usually accepted as a water temperature change of 1 ºC or greater per meter of water depth (Wetzel 1983). To address standard attainment the minimum, water column average, for comparison to modeling results, and surface average DO, in temperature stratified reaches, were evaluated. As presented in Table 2.2, observed DO concentrations for Pecan Creek were within applicable standards (Table 2.1). Excursions outside of the DO water quality standards for Pecan Creek did not occur at the sites monitored. Although the minimum value measured at 6,856 m downstream from the discharge was below the standard minima of 3.0 mg/L, the minimum value was measured in the hypolimnion, not in the epilimnion. Therefore, DO monitoring data indicate that PCWRP effluent loadings of BOD and NH_3-N were not causing nonattainment of the Pecan Creek DO water quality standards.

Water Chemistry

Pecan Creek water chemistry results for the summer of 1997 are summarized in Table 2.3, for chlorophyll a, and in Table 2.4 for other important parameters. Water chemistry results were utilized to build model datasets to predict DO concentrations throughout the Pecan Creek reaches downstream from the PCWRP discharge. Data collected for the summer of 1997 were utilized to compare model results to actual field conditions. Using this approach, model parameters were calibrated to yield comparable model profiles to field measured chemistry profiles. In general, the most important parameters for model development were BOD_5, NH_3-N, Nitrate + Nitrite (NO_3+NO_2), total kejhdal nitrogen (TKN), total phosphate (TP), ortho-phosphate (OP), and chlorophyll a.

Chlorophyll a showed trends of increasing concentration with distance downstream (Figure 2.5). The occurrence of a storm event prior to the August 21, 1997 sampling event resulted in the reduction of average chlorophyll a in the lentic reaches of Pecan Creek, at 5,134 m and 5,900 m downstream from the PCWRP discharge. These data indicate that chlorophyll a patterns are disrupted following a storm event, however, average chlorophyll a concentrations returned to pre-storm event conditions by August 28, 1997. The July 31, 1997 data set was used for calibration of the QUAL2E model and the other data sets were used for evaluation, excluding those influenced by storm events.

Physical Stream Measurements

Physical stream measurements indicated that the background flow (m^3/s) was minimal during the summer of 1997. Measured flow was 0.026 m^3/s on June 28, 1997 and total stream flow downstream from PCWRP was 0.524 m^3/s. Background flow accounted for less than 5% of the total instream flow downstream from the WRP. This was again observed in August of 1998, as background flow was about 0.008 m^3/s and total flow downstream from the PCWRP was 0.421 m^3/s (1.7% of total). A summary of physical stream measurements is provided in Table 2.5. Physical stream measurements were used to define the stream reaches within the model. Accordingly, the model dataset had six stream reaches based on morphology, depth, and velocity of flow. Following model set development, Reach 5 was subdivided to allow for more accurate modeling at the DO sag point. Therefore, the final model was divided into 7 reaches based on physical and water quality characteristics.

Water Quality Modeling

Model Development. A QUAL2E model dataset was developed from the summer 1997 data and the model used to predict DO in Pecan Creek. Previous modeling to evaluate Pecan Creek did not include a sufficient algae component that could accurately predict increased epilimnion average DO, due to algae productivity, in the backwater areas (Rudolph 1999). Model calibration entailed development of a dataset for the QUAL2E model to include an algae component that could predict DO values measured in Pecan Creek in the summer of 1997. Specifically, one set of data, July 31, 1997, was used to calibrate the model to observed PCWRP loadings. Model calibration was the parameterization of stream velocity and depth coefficients and exponents, algae rates, and the adjustment of these and other components to accurately predict DO in Pecan Creek, especially the backwaters. The model parameter set was then evaluated by adjusting the background and effluent model conditions to observed values, for the various water quality monitoring events in 1997 and 1998, to assess the prediction of DO in Pecan Creek. Evaluation of the calibrated Pecan Creek QUAL2E model set served to validate the use of the model over a temporal and spatial scale. Other data sets for 1998 and 1999 were not used because the specified TNRCC Lake Lewisville summer pool criterion was not met. Additionally, these data showed a completely different DO regime for Pecan Creek, due to a change from lentic to lotic conditions.

This model development followed conditions specified by TNRCC for evaluation of DO standard attainment. DO standard attainment was assessed and defined by a lake elevation of 522 feet above mean sea level. Pecan Creek above 522 feet elevation is considered to be advective, whereas below an elevation of 522 feet Pecan Creek is considered lentic. Accordingly, in July and August of 1997, and June of 1998, Lake Lewisville met these conditions and the model could be assessed. In the remainder of 1998 and 1999 the Lake elevation dropped significantly and produced lotic conditions throughout most of Copas Cove, as previously shown. Therefore, stratified conditions did not occur in Pecan Creek and the backwater conditions were inconsistent with those that occurred in the summer of 1997. It was assumed that worst-case conditions occurred when backwater stratified conditions were present at or near Lake Lewisville summer pool elevation of 522 feet above mean sea level.

Model calibration and evaluation. A Microsoft© Windows version of the QUAL2E model was obtained from the U.S. EPA's Office of Water internet site (USEPA 1995). The model was calibrated using data obtained during 1997, and evaluated with data sets collected in 1997 and 1998. Inputting the conditions observed during the critical summer period for July 31, 1997 completed parameterization of the model. Calibration required adjustments to sensitive parameters in order to predict the DO previously observed in Pecan Creek. Each time model parameters were adjusted the results were assessed to determine how well the model predicted observed conditions. Calibrated model results for surface and water column average DO values for the July 31, 1997 showed a good fit to actual observed DO data (Figure 2.6). A 0.57% difference was observed between water column average DO (24-hour average) and model predicted DO at the sag point. Calibration indicated that the QUAL2E model was capable of predicting elevated water column average DO concentrations resulting from stratified conditions and algae productivity in downstream lentic zones. As such, the QUAL2E model was parameterized to predict the water column 24-hour average DO (mg/L) conditions in

Pecan Creek. However, it is noted that the model under predicted the epilimnion or surface average DO (mg/L) conditions. Moreover, the model adequately predicted DO (mg/L) values in the open waters of the Lake Lewisville cove, with exception of the last monitoring station (6,856 m downstream from the effluent discharge). The downstream most monitoring site typically exhibited reduced secchi depths, elevated TSS, and reduced DO as a result of suspended sediments and associated oxygen demand. These characteristics define that site as being influenced by the open waters of Lake Lewisville.

TNRCC regulations apply the 5.0 mg/L DO standard to the epilimnion or surface layers under stratified lake conditions, therefore a method for relating water column DO to epilimnion DO was needed. Results from the model were the prediction of water column average DO values. Predicted water column DO values were related to epilimnion values by a linear regression method. Therefore, the WLA was assessed in comparison to the related epilimnion average DO values.

To evaluate the model the observed variables were changed, such as effluent DO, flow, background concentrations, and water quality, to reflect other data sets collected in 1997 and June of 1998. Results of the model were compared to the observed DO and the percent difference at the sag point compared. Adjustment of parameters were made to reduce the percent difference to a minimum. Results are shown in Table 2.6 and indicate that the calibrated model adequately predicted observed conditions for the other data sets. Overall, the model predicts observed DO conditions at the sag within 11.51% of the water column averages for all data sets. Lastly, these projections were made at impounded conditions for Pecan Creek, therefore as close as possible to the regulatory Lake Lewisville pool level of 522 feet above mean sea level. This Lake level is considered the regulatory critical condition with a reduced advective reach and a point of maximal impact (sag).

As a result of the 11.51% maximum observed difference between model predicted DO and observed values, a 12% safety factor has been applied to final WLA model set results. In this manner, the observed differences between model DO projections and observed data were accounted for. Additionally, this safety factor can be assessed once the PCWRP discharge upgrades are made and effluent flows and loadings increase. Future monitoring may indicate that the safety factor should be increased or decreased, accordingly.

Sensitivity analysis. Using the built-in QUAL2E-UNCAS First Order Error Analysis module of the U.S. EPA's QUAL2E water quality model, a sensitivity analysis was performed (Brown and Barnwell 1987). Sensitivity analysis results are shown in Table 2.7. Results of the sensitivity matrix represent the percent change in DO caused by a 1% change in the parameter. The parameters found to cause the most variability in the modeled DO (mg/L), within the critical reaches, were algae maximum growth rate (AGYGROMX), atmospheric pressure (ATMPRES), BOD decay, Sediment Oxygen Demand (SOD) rate, chlorophyll *a* to algae ratio (CHLA/ART), and initial stream temperature (INITTEMP). Other parameters found to be sensitive within the model set were coefficients and exponents for flow (velocity), number of daylight hours, and point load NH_3-N. Although point load BOD is not listed in Table 2.6 it had a significant impact on the DO, especially in combination with flow and ammonia point load impacts from PCWRP.

Parameters that were adjusted to better parameterize the model were algae maximum growth rate, and the coefficients and exponents for flow (velocity). Point load variables were measured and were therefore set in the model. Other sensitive parameters were set as constant in the model according to default or accepted values (Brown and Barnwell 1987; Thomann and Mueller 1987; Environmental and Hydraulics Laboratory, USCOE 1994). Parameters in the model represent measured values, literature values or best professional judgments. Projections with the model have relied on adjusting the point loads to determine the acceptable loadings from the PCWRP that will not impair the DO water quality in Pecan Creek. Additionally the point-load DO (mg/L), temperature (ºC), and atmospheric pressure were sensitive in the model but these again were measured and are set in the model.

When applied to the PCWRP discharge the permitted loadings can be input into the Pecan Creek QUAL2E model set to predict the water column average DO in Pecan Creek and the Lake Lewisville Arm of Pecan Creek. With further application of the relationship between observed water column average DO and epilimnion average DO conditions, a linear regression method was used to determine regulatory attainment of the DO standard. Thus, a linear regression method allowed water column predictions to be made, assessed as to the epilimnion DO concentrations, and the acceptable loading to meet the 5.0 mg/L standard determined.

Wasteload Allocation

The determination of a WLA for Pecan Creek was dependant upon the applicable regulations, the loadings to the stream, model data, and the ambient water quality characteristics. Additionally, a WLA provides a predictive tool to assess future effluent loading scenarios from PCWRP, and project NPDES permit limits protective of DO standards. This section provides the results of the WLA analysis and presents a method for relating modeled water column average DO to epilimnetic DO for standard attainment.

Regression Analysis of Epilimnetic DO. A problem that existed with using a stream water quality model, like QUAL2E (Brown and Barnwell 1987), was predicting the elevated epilimnetic DO. Typically, the epilimnion exhibits greater fluctuations in DO and temperature, and has an associated algae community which may cause DO values in excess of 100% saturation throughout daylight hours in summer (Wetzel 1983). However, preliminary results indicated that the model would adequately predict water column average DO conditions. Thus, a method was established to relate epilimnion DO to water column average DO.

A linear regression analysis of water column and epilimnion average DO was completed. Data from all sites in 1997, July through August, that exhibited temperature stratification, thus discontinuous layers, were utilized for the analysis. The epilimnion was taken as being the layer of water from the surface to a depth which exhibited greater than 1°C change over one meter of depth. Average conditions for the epilimnion were calculated as the average of DO values measured only in the epilimnion over the monitoring period. The water column average DO was taken as the average of DO values for all depths at a monitoring site over the monitoring period.

To allow for the association of QUAL2E predicted water column average DO to epilimnion average DO for standard attainment, a method was needed to relate water column and epilimnion DO values. The solution was to combine water column and epilimnion average DO values for the summer of 1997 and perform a regression analysis to assess the relationship. It was assumed that surface average DO would be related to water column values by a linear equation.

By selecting water column average DO as the independent variable and epilimnion average DO as the dependent variable, a regression analysis was performed (Figure 2.7). The analysis indicated that the relationship followed a linear regression with an r^2 value of 0.81. Thus, the relationship showed a high level of correlation, with over 80% of the variability in water column DO (mg/L) explained by the epilimnion average DO (mg/L). Considering that the analysis consisted of combining data for all sites exhibiting stratification in 1997 the regression results indicate a strong correlation. From the analysis, the following equation was developed to relate QUAL2E water column average results to epilimnion average values for WLA development.

$$\text{Epilimnion Avg. DO} = (1.71 * \text{Water Column Avg. DO}) - 2.21$$

$$r^2 = 0.81$$

<u>Wasteload Allocation Projections</u>. Wasteload allocation (WLA) projections for PCWRP were made with the evaluated Pecan Creek QUAL2E model set. This model set includes PCWRP and Denton Municipal Power Plant (Power Plant) as point source discharges. Previous modeling did not include the Power Plant but it was incorporated to create a more comprehensive model. This model set may enable varied discharge scenarios and Total Maximum Daily Loads (TMDLs) to be evaluated.

Data was not collected as part of this project for the Power Plant or for Pecan Creek upstream from the Power Plant. However, data collected by the City of Denton were reviewed and used to characterize the Power Plant point source discharge. Data for

Pecan Creek upstream from PCWRP were used in conjunction with the Power Plant data to perform a mass balance of the Pecan Creek headwater. Observations of Pecan Creek indicated that during summer Pecan Creek may have no flow or associated loadings upstream from PCWRP. This was witnessed in September of 1999 once the Denton Municipal Power Plant went to zero discharge to Pecan Creek. Therefore, this model and the WLA results not only account for PCWRP but account for the Power Plant by using permitted flow, and worst case measured BOD_5 and ammonia values and the observed Pecan Creek water quality (DO). City of Denton data for the power plant indicated that the maximum monthly average BOD_5 (mg/L), NH_3-N (mg/L), and Total Phosphorus (mg/L) were, 12.6, 0.88, and 33.14, respectively. Permitted flow for the Power Plant was 1.2 MGD. Loadings of Total Phosphorus were excessive from the Power Plant. However, the limited flow and intermittent nature of the discharge reduced impacts.

Projecting water quality at the current permitted loadings for flow, BOD_5, and NH_3-N for PCWRP and the Power Plant performed the first part of WLA modeling. To complete WLA modeling the current Power Plant permitted loadings and the future PCWRP loadings were modeled. Model flows of 21, 25, and 30 mgd from PCWRP were used at various loading scenarios for BOD_5 and NH_3-N to determine the PCWRP effluent loadings to protect the 5.0 mg/L DO standard in Lake Lewisville. All the while, the Power Plant loadings were set at the current permitted flows and the worst-case (maximum monthly average) measured water quality. In this manner, we assumed the worst case for the Power Plant discharge with a minimum headwater flow and calculated loadings.

Final WLA projections were done by utilizing the model and varying the PCWRP effluent flow, BOD_5, and NH_3-N and predicting water column average conditions for DO. In assessing WLA projections the minimum DO value in the impounded backwater area of Pecan Creek was utilized as the point of attainment. Therefore, a 5.0 mg/L DO standard was the assessment benchmark for comparison, except in spring the value utilized was 5.5 mg/L (TNRCC 1997). Also, an 8-hour period of DO (mg/L) to a value of 4.0 mg/L is allowed by TNRCC, but this was not utilized for assessing attainment. Critical temperature conditions were determined for a regional reference stream and the PCWRP effluent and applied within the model. Critical temperatures for Pecan Creek and the PCWRP effluent were determined to be 32.7 ºC and 30.5 ºC. Historical temperature data did not exist for Pecan Creek, as it is has no gaging station. Field measurements of temperatures for Pecan Creek were in agreement with results from the reference stream (Clear Creek).

QUAL2E Pecan Creek WLA model results for an effluent flow of 21 mgd, and NH_3-N values of 2.0 mg/L and 3.0 mg/L were used to evaluate future PCWRP expansions (Figures 2.8 and 2.9). Under these conditions it was observed that the model indicated a BOD_5 range of 4.8 to 10.3 mg/L to meet the 5 mg/L DO standard, in summer. Following review of data and wastewater treatment efficiencies, it was determined that effective upgrades could provide for a facility to treat to a BOD_5 of 7.0 mg/L. By entering a BOD_5 concentration of 7 mg/L into the model set and a flow of 21 mgd, the PCWRP effluent NH_3-N concentration was varied to address the impact of ammonia for NPDES permitting. Results of these model runs are shown in Figure 2.10. From these runs and by inputting the resulting NH_3-N (mg/L) concentration into the model, it was determined that a concentration of 2.6 mg/L would achieve the 5 mg/L DO standard.

Summer conditions were evaluated with the model as these produced the minimum DO values observed, even when projecting those results to the epilimnion average DO. Thus, the water column average results were input into the equation relating water column to epilimnion DO and projected to epilimnion average DO values. In this manner, results of the model could be compared to actual standard attainment conditions.

Modeling was done at the flow expected for PCWRP following facility upgrades. It is anticipated that as the population within the City of Denton increases that the wastewater service area will expand. PCWRP upgrades are necessary as population forecasts for the region indicate a necessary expansion of the City of Denton's wastewater treatment services (Figure 2.11). By the year 2020 the human population is expected to reach over 150,000. This is forecasted to result in a needed peak wastewater treatment plant flow in excess of 21 mgd.

Following the model runs and development of results, an assessment of PCWRP wastewater treatment scenarios was completed. After review of the data and confirmatory modeling it was determined that a PCWRP discharge scenario of 7.0 mg/L BOD_5 and 2.6 mg/L NH_3-N at 21 mgd flow would meet the 5.0 mg/L DO standard during the critical summer season. Therefore, an NPDES permit that would optimize NH_3-N (mg/L) and BOD_5 (mg/L) loadings for the calibrated model set, while sustaining the DO standard, would be a 7/10/2.6 (BOD_5, TSS, NH_3-N) at a 21 mgd flow. By application of the 12% safety factor to the NH_3-N loadings the permit for the PCWRP would be 7/10/2.3 (mg/L BOD_5, TSS, NH_3-N) at a 21 mgd flow. Use of the 12% safety factor serves to protect the aquatic resources from model uncertainty. The safety factor was only applied to NH_3-N loadings as a change in other loadings would result in a larger margin of safety.

Discussion

This study was done to assess the impacts of the PWRP effluent discharge on water quality in Pecan Creek. Objectives of the study were to determine the current water quality characteristics of Pecan Creek, assess the impact of the PCWRP discharge on Pecan Creek water quality during critical summer low-flow and high temperature scenarios, and project PCWRP loadings of BOD_5 and NH_3-N that would attain DO standards at future effluent discharge flows, thus determine a WLA for the PCWRP. Likewise, this research provided a unique case study of an effluent dominated intermittent stream entering a backwater area of a reservoir and assessed the application of the QUAL2E, under these conditions. The occurrence of point and nonpoint sources entering intermittent streams is common in Texas, yet relatively few water quality studies exist that demonstrate characteristics of these streams and WLA development.

Analyzing DO, temperature, and water chemistry data determined the condition of Pecan Creek water quality. Monitoring results indicated that the effluent loading scenarios observed did not cause DO levels to fall below the 5 mg/L standard. Although Pecan Creek is an effluent dominated intermittent stream, water quality was maintained by adequate treatment of wastewater from PCWRP. Under conditions observed in 1997 the PCWRP could attain and maintain DO water quality goals in Pecan Creek.

To fully assess the impact of the PCWRP loadings, under conditions observed in 1997, a data set was developed for the QUAL2E model. Water quality modeling results for Pecan Creek and the associated point source loadings, under summer base flow conditions, indicated that DO water quality could be attained. Major factors determined to influence the Pecan Creek system were PCWRP flow, loadings of BOD_5, and NH_3-N, instream algae dynamics, and temperature. PCWRP constituted about 95% or more of the flow in Pecan Creek from the point of effluent discharge. Therefore, the effluent discharge of BOD_5, NH_3-N, and nutrients to Pecan Creek exerts the greatest influence on instream DO.

Model results confirmed the effluent discharge as the controlling factor for Pecan Creek water quality. This was witnessed by the increases in summer instream DO downstream from the discharge and the modulation of other water quality and water chemistry parameters. The PCWRP effluent discharge has the most prominent influence on Pecan Creek water quality through the lotic reaches, prior to Lake Lewisville. However, prevailing backwater conditions in the summer of 1997 and June of 1998 were observed to exert a direct influence on DO water quality. This influence tended to increase the variability in water column DO and produce stratified conditions. As such, the loadings from the PCWRP had the greatest influence at a point approximately 4,000 to 5,000 m downstream from the effluent discharge, at or near full summer pool for Lake Lewisville. This transition zone represents the critical area most vulnerable to PCWRP and other point source loadings at a Lake Lewisville surface elevation at or near 522 feet above mean sea level.

To address future loadings of BOD_5 and NH_3-N from the PCWRP water quality modeling was completed. Model runs were made with the QUAL2E data sets developed from the 1997 monitoring data. Thus, a calibrated and evaluated model set was used to predict the impacts of the facility upgrades to a 21 mgd effluent discharge. Calibrated model projections of water quality indicated that a discharge of 7.0 mg/L BOD_5, 2.6 mg/L NH_3-N, and 6.0 mg/L of DO, at a flow of 21 mgd, would maintain instream DO within acceptable water quality limits. However, application of the additional 12% safety factor would lower the NH_3-N concentration to 2.3 mg/L. Use of the safety factor is recommended to protect aquatic resources. However, based upon strict adherence to the Texas DO water quality standards and in consideration of 12% as the maximum percent difference (model DO to observed DO), the 12% safety factor may be overly stringent. Texas DO water quality standards allow for an 8-hour period, during a daily cycle, for instream DO values to fall below the 5.0 mg/L standard to a minimum of 4.0 mg/L. Thus, WLA projections for Pecan Creek include an automatic level of safety by modeling to a target of 5.0 mg/L DO.

Future loadings, when applied to a critical zone occurring at a Lake Lewisville pool elevation at or near 522 feet above mean sea level, have the potential to cause nonattainment of the DO standard. These loadings should be monitored for the impact to instream DO and assessed with the calibrated model set. Model results indicated that application of the QUAL2E model to backwater scenarios could be accomplished with attention to impoundment stratification and spatial gradients in water quality. Also, algae dynamics, as measured by Chlorophyll *a*, were found to be a controlling factor for Pecan Creek DO water quality within the model. This begs the question: Will changes in wastewater treatment resulting in nutrient reductions in the PCWRP effluent provide for greater protection of Lake Lewisville water quality?

Water quality observations for the portion of Lake Lewisville receiving flows from Pecan Creek indicate that much is to be learned about the influence of PCWRP discharge on Lake Lewisville water quality. As the population in Denton increases and effluent loadings increase these dynamics may change. Future monitoring and assessments of Pecan Creek water quality will be needed to quantify these changes. Additionally, the influence of the PCWRP loadings on phytoplankton and bacteria dynamics within Pecan Creek should be studied to determine best management practices for the facility. Observations showed that nutrient levels were reduced from the point of PCWRP discharge and downstream into Lake Lewisville. Additionally, increases in BOD_5, DO variability, and chlorophyll *a* in the backwater regions indicated that phytoplankton dynamics are influenced by the PCWRP discharge. As such, water quality dynamics change in conjunction with changes in the biological community. Future studies to quantify the bacteria and phytoplankton community and seasonal dynamics may shed light on ways to optimize the PCWRP effluent discharge.

As an intermittent urban stream Pecan Creek represents a common case across much of Texas. Future research of Pecan Creek will increase the ability of environmental managers, scientists, and regulators to deal with water quality challenges in these situations in North Texas and other parts of the country. Lastly, to promote a more holistic watershed management paradigm, nonpoint source contributions should be assessed as to temporal and spatial impacts on Pecan Creek water quality.

References

1. Arar, E. J. and G. B. Collins. 1992. "Method 455.0 In Vitro Determination of Chlorophyll a and Pheophytin a in Marine and Freshwater Phytoplankton by Fluorescence." *Methods for the Determination of Chemical Substances in Marine and Estuarine Environmental Samples*. EPA/600/R-92/121. Cincinnati, OH: USEPA, Environmental Monitoring Systems Laboratory, Office of Research and Development.

2. Atkinson, S. F., K. L. Dickson, G. D. Maschmann, R. D. Taylor, J. Coulter, and G. Stover. 1997. *Water Quality Assessment of City of Denton's WWTP Effluent on Pecan Creek and Lake Lewisville*. Denton, Texas: University of North Texas.

3. Brown, L. C. and T. O. Barnwell. 1987. *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual*. Athens, Georgia: U.S. Environmental Protection Agency, Office of Research and Development.

4. Buchanan, T. J. and W. P. Somers. 1965. "Discharge Measurements at Gaging Stations." Book 3 - Techniques of Water Resources Investigations. Reston, Va: United States Geological Survey.

5. City of Denton. 1999. "Planning and Development: Population Projections 1998 - 2020" [Web Page]. Accessed 7 Sep 1999. Available at http://www.ci.denton.tx.us/planning/popprojections.html.

6. Cleveland, K. D. 1991. "Analysis of Wastewater Discharges to Backwater Areas." Final Draft ed. Texas Water Commission, Environmental Systems Section.

7. Coulter, J. 1999. "Report to TNRCC for Review of Plant Expansion." July ed. Denton, Texas: City of Denton.

8. Driscoll, E. D., J. L. Mancini, and P. A. Mangarella. 1983. "Technical Guidance Manuel for Performing Waste Load Allocations." Pp. 263 in , vol. EPA-440/4-84-020Washington, D.C.: USEPA.

9. Environmental and Hydraulics Laboratory, USCOE. 1994. "CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality." Pp. 57 in . 1994 ed.Vicksburg, MS: U.S. Army Engineers Waterways Experiment Station.

10. Gilbert, R. O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. New York, NY: Van Nostrand Reinhold Co.

11. Karr, J. R. 1991. "Assessment of Biotic Integrity Using Fish Communities." *Fisheries* (6):21-27.

12. ———. 1999. "Defining and Measuring River Health." *Freshwater Biology* (41):221-24.

13. Kelly, L. A., J. Stellwagen, and A. Bergheim. 1996. "Waste Loadings From a Freshwater Atlantic Salmon Farm in Scotland." *Water Resources Bulletin* 32(5):1017-25.

14. Korfmacher, K. S. 1998. "Water Quality Modeling for Environmental Management: Lessons From the Policy Sciences." *Policy Sciences* 3135-54.

15. Leopold, Aldo. 1949. *A Sand County Almanac and Sketches Here and There*. New York, NY: Oxford University Press, Inc.

16. Norris, R. H. and M. C. Thoms. 1999. "What Is River Health?" *Freshwater Ecology* (41):197-209.

17. Park, S. S. and C. G. Uchrin. 1996. "Waste Load Allocation for a Macrophyte Growing Impoundment: a Combined Modeling Approach." *Journal of Environmental Science and Health* 31(2):411-28.

18. Shapiro, S. S. and R.S. Francia. 1972. "An Approximate Analysis of Variance Test for Normality." *Journal of the American Statistical Association* 67(337):215-19.

19. Taylor, R. D., S. A. Atkinson, K. L. Dickson, G. Maschmann, J. Coulter, and V. Verbosh. 1999. *Pecan Creek Water Quality Study: Phase 2*. January 14 ed. Denton, TX: University of North Texas.

20. Thomann, R. V. and J. A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. New York, New York: HarperCollinsPublishers Inc. 644 pp.

21. TNRCC. 1997. "Chapter 307, Texas Water Quality Standards." Austin, Texas. §307.7. Site-Specific Uses and Criteria..

22. ———. 1999. *Methodology for Establishing Surface Water Quality Priorities for Texas River Basins*. Draft ed. Austin, Texas: TNRCC.

23. Turner Designs. 1994. *A Procedure for Measuring Extracted Chlorophyll a Free From the Errors Associated With Chlorophyll b and Pheopigments*. Sunneyvale, CA: Turner Designs.

24. USEPA. 1999. "Guidance for Water Quality-Based Decisions: The TMDL Process" [Web Page]. Accessed 31 Mar 1999. Available at http://www.epa.gov/OWOW/tmdl/decisions.

25. ———. 1995. "QUAL2E Windows Interface User's Guide." . EPA/823/95/003 ed.Washington, D.C.: USEPA, Office of Water.

26. ———. 1991. "Technical Support Document For Water Quality-Based Toxics Control." Pp. 145 in , vol. EPA/505/2-90-001Washington, D.C.: Office of Water.

27. Warwick, J. J. and L.A. Roberts. 1992. "Computing the Risks Associated With Wasteload Allocation Modeling." *Water Resources Bulletin* 28(5):903-15.

28. Welschmeyer, N. A. 1994. "Fluorometric Analysis of Chlorophyll a in the Presence of Chlorophyll b and Pheopigments." *Limnology and Oceanography* 39(8):1985-92.

29. Wetzel, R. G. 1983. "Limnology." Pp. 767 in . Second ed. New York, NY: Saunders College Publishing.

Table 2.2 Summary statistics for Pecan Creek DO (mg/L) during the summer of 1997 for all water quality monitoring stations.

Statistic	-231 m	+643 m	+1762 m	+3900 m	+4300 m
Min	2.77	5.66	5.77	4.60	4.45
Mean	5.16	6.73	6.93	6.60	7.64
Median	5.06	6.50	6.95	6.42	6.80
Max	7.6	8.26	8.17	9.14	20.0
N	20	21	21	47	62
Std Dev	1.4	0.75	0.73	1.14	3.25
1st Quartile	4.23	6.20	6.32	5.60	5.79
3rd Quartile	6.32	7.32	7.50	7.44	7.47

Statistic	+5,134 m	+5,900 m	+6,400 m	+6,856 m
Min	4.45	4.81	3.68	2.02
Mean	8.10	7.87	7.06	6.84
Median	7.40	7.32	6.75	7.36
Max	20.0	16.95	17.32	15.03
N	59	74	92	49
Std Dev	3.58	3.05	2.78	2.72
1st Quartile	5.89	5.72	4.80	4.80
3rd Quartile	7.73	8.73	8.27	8.31

Table 2.3 Chlorophyll a concentrations in Pecan Creek, summer 1997.

Distance Downstream (m) (1)	Chlorophyll *a* (2) (μg/L)					
	24-Jul-97	31-Jul-97	21-Aug-97	28-Aug-97	4-Sep-97	19-Sep-97
-231	5.7	5.0	6.1	6.1	6.8	1.2
0	0.4	2.1	1.1	1.5	1.4	1.8
1762	5.7	2.1	2.3	1.5	5.0	0.7
5134	34.5	26.7	8.9	27.1	11.3	2.5
5900	21.0	15.3	13.2	30.3	13.9	8.5
6400	23.9	16.7	24.6	40.9	24.6	31.7

(1) Locations upstream from the WRP discharge are indicated by negative distance values and those downstream are indicated by positive distance values.
(2) Average values of three samples collected at the water surface, approximately 0.3 m of depth.

Table 2.4 Summary statistics for Pecan Creek water chemistry, summer 1997. Locations upstream from the WRP discharge are indicated by negative distance values and those downstream are indicated by positive distance values.

Site	Statistic	BOD_5 (mg/L)	NH_3-N (mg/L)	NO_3+NO_2 (mg/L)	TKN (mg/L)	TP (mg/L)	OP (mg/L)
-231 m	Min	1.50	0.07	0.20	0.35	0.003	0.003
	Mean	3.63	0.22	8.90	1.25	1.05	0.73
	Median	2.70	0.18	8.71	1.06	1.14	0.48
	Max	8.10	0.50	20.08	2.80	2.09	1.80
	N	7	6	8	5	8	8
	Std Dev	2.41	0.16	8.18	0.92	0.70	0.72
	1st Quartile	1.95	0.09	1.52	0.90	0.62	0.20
	3rd Quartile	4.60	0.27	15.28	1.12	1.33	1.16

0 m Effluent	Min	2.10	0.04	13.10	0.65	1.37	1.13
	Mean	2.71	0.23	16.14	1.35	2.30	1.82
	Median	2.40	0.20	16.47	1.14	2.44	1.91
	Max	3.80	0.50	18.78	2.52	2.95	2.54
	N	7	6	8	6	8	8
	Std Dev	0.76	0.17	1.89	0.76	0.53	0.53
	1st Quartile	2.15	0.10	15.25	0.72	1.99	1.36
	3rd Quartile	3.20	0.32	17.33	1.82	2.68	2.18

1,762 m	Min	1.60	0.10	6.90	0.60	0.60	0.52
	Mean	3.08	0.22	15.08	1.19	2.08	1.49
	Median	2.40	0.18	16.86	1.03	2.29	1.64
	Max	5.80	0.50	19.75	2.24	3.34	2.37
	N	5	6	8	6	8	8
	Std Dev	1.69	0.15	4.32	0.57	0.92	0.65
	1st Quartile	2.00	0.13	12.78	0.90	1.48	0.98
	3rd Quartile	3.60	0.15	17.73	1.31	2.53	1.93

5,134 m Surface	Min	1.80	0.12	2.28	0.99	0.57	0.31
	Mean	3.79	0.34	10.10	1.61	1.55	1.10
	Median	3.90	0.25	11.70	1.30	1.54	0.85
	Max	5.10	0.78	16.31	2.80	3.00	2.34
	N	7	6	8	6	8	8
	Std Dev	1.39	0.25	5.42	0.74	0.78	0.73
	1st Quartile	2.90	0.16	5.76	1.07	1.01	0.54
	3rd Quartile	4.95	0.45	14.02	2.03	1.89	1.64

5,134 m Bottom	Min	1.40	0.16	7.36	0.52	1.33	0.88
	Mean	2.97	0.54	13.50	1.39	2.00	1.24
	Median	3.00	0.20	15.10	1.38	1.88	1.63
	Max	5.20	2.02	16.31	2.02	3.12	2.52
	N	7	6	8	6	8	8
	Std Dev	1.32	0.74	4.06	0.55	0.53	0.59
	1st Quartile	2.00	0.17	11.19	1.18	1.76	1.24
	3rd Quartile	3.60	0.43	16.28	1.80	2.17	2.09

Table 2.4 continued.

Site	Statistic	BOD_5 (mg/L)	NH_3-N (mg/L)	NO_3+NO_2 (mg/L)	TKN (mg/L)	TP (mg/L)	OP (mg/L)
5,900 m Surface	Min	2.80	0.11	2.29	0.91	0.29	0.11
	Mean	3.88	0.30	9.23	1.07	1.35	1.05
	Median	3.80	0.27	9.46	1.03	1.11	1.05
	Max	5.00	0.50	16.26	1.35	3.00	2.22
	N	7	6	8	6	8	8
	Std Dev	0.74	0.16	5.20	0.15	0.93	0.76
	1st Quartile	3.45	0.17	6.03	1.00	0.70	0.45
	3rd Quartile	4.35	0.44	12.62	1.10	1.88	1.52

5,900 m Bottom	Min	2.20	0.06	0.05	0.79	0.88	0.59
	Mean	3.75	0.52	10.34	1.84	2.20	1.77
	Median	3.30	0.22	10.85	1.70	2.18	1.76
	Max	6.90	0.78	16.93	3.08	4.12	3.82
	N	8	6	8	6	8	8
	Std Dev	1.51	0.72	5.10	0.96	1.08	1.09
	1st Quartile	3.00	0.18	9.10	1.07	1.29	0.93
	3rd Quartile	4.95	0.43	14.02	2.62	2.69	2.22

6,400 m Surface	Min	2.40	0.14	0.35	0.81	0.06	0.003
	Mean	3.83	0.29	4.91	1.08	0.80	0.45
	Median	3.50	0.26	4.48	1.00	0.46	0.17
	Max	5.60	0.50	10.45	1.40	2.33	1.79
	N	8	6	8	5	8	8
	Std Dev	0.99	0.14	4.22	0.23	0.84	0.61
	1st Quartile	3.30	0.20	0.87	1.00	0.16	0.07
	3rd Quartile	4.45	0.38	8.76	1.21	1.25	0.61

6,400 m Bottom	Min	2.70	0.11	0.26	1.00	0.65	0.53
	Mean	4.14	0.52	8.52	1.37	1.65	1.31
	Median	3.75	0.25	9.05	1.30	1.82	1.30
	Max	7.60	1.85	14.78	1.96	2.33	2.03
	N	8	6	8	5	8	8
	Std Dev	1.62	0.67	4.50	0.36	0.58	0.57
	1st Quartile	2.95	0.18	6.93	1.21	1.30	0.07
	3rd Quartile	4.63	0.45	11.13	1.40	2.08	0.61

Table 2.5 Hydraulic characterization of Pecan Creek, July 1997

Reach	**Distance (m)**	**Cumulative TOT (1) (hours)**	**Average Depth (m)**	**Area (m^2)**	**Average Velocity (m/s)**	**Flow (2) (m^3/s)**
1	874	3.03	0.49	6.16	0.08	0.48
2	1019	4.64	0.56	2.89	0.18	0.51
3	923	5.33	0.24	1.67	0.37	0.62
4	1614	12.80	0.77	8.20	0.06	0.50
5	1586	39.11	1.89	31.26	0.02	0.50

(1) Cumulative TOT = Cumulative Time of Travel of water through Pecan Creek.
(2) Reach 6 had no measurable flow, lentic conditions in open water of cove.

Table 2.6 QUAL2E model set evaluation, comparison of measured and predicted DO (mg/L) at the sag point in Pecan Creek.

Data Set	**Measured DO at Sag (mg/L)**	**Predicted DO at Sag (mg/L)**	**Percent Error**
July 31, 1997 -Calibration Set	6.96	6.92	0.57%
July 17, 1997	6.61	6.94	-4.99%
July 24, 1997	6.81	6.88	-1.03%
June 24, 1998	6.34	7.07	-11.51%

Table 2.7 Sensitivity and variance matrix results for the calibrated QUAL2E model set. Analysis of sensitivity and variance was made at the point of DO (mg/L) sag. Model parameters with sensitivity at or near ±1.0% are shown.

Input Variable	**Impact on DO**
Sensitivity	**% Change in DO per 1% Change in Input**
ATMPRES	1.072
INITTEMP	-0.878
(all other variables caused minimal sensitivity)	
Variance	**% Affect on DO Variance**
AGYGROMX	1.52
ATMPRES	24.5
BOD Decay	1.15
SOD Rate	1.65
CHLA/ART	1.77
INITTEMP	65.76
Sum	**96.35**

AGYGROMX = Agal Maximum Specific Growth Rate
ATMPRES = Atmospheric Pressure
BOD Decay = BOD Decay
SOD = Sediment Oxygen Demand Rate
CHLA/ART = Chlorophyll a to Algae Mass Ratio
INITTEMP = Initial Stream Temperature

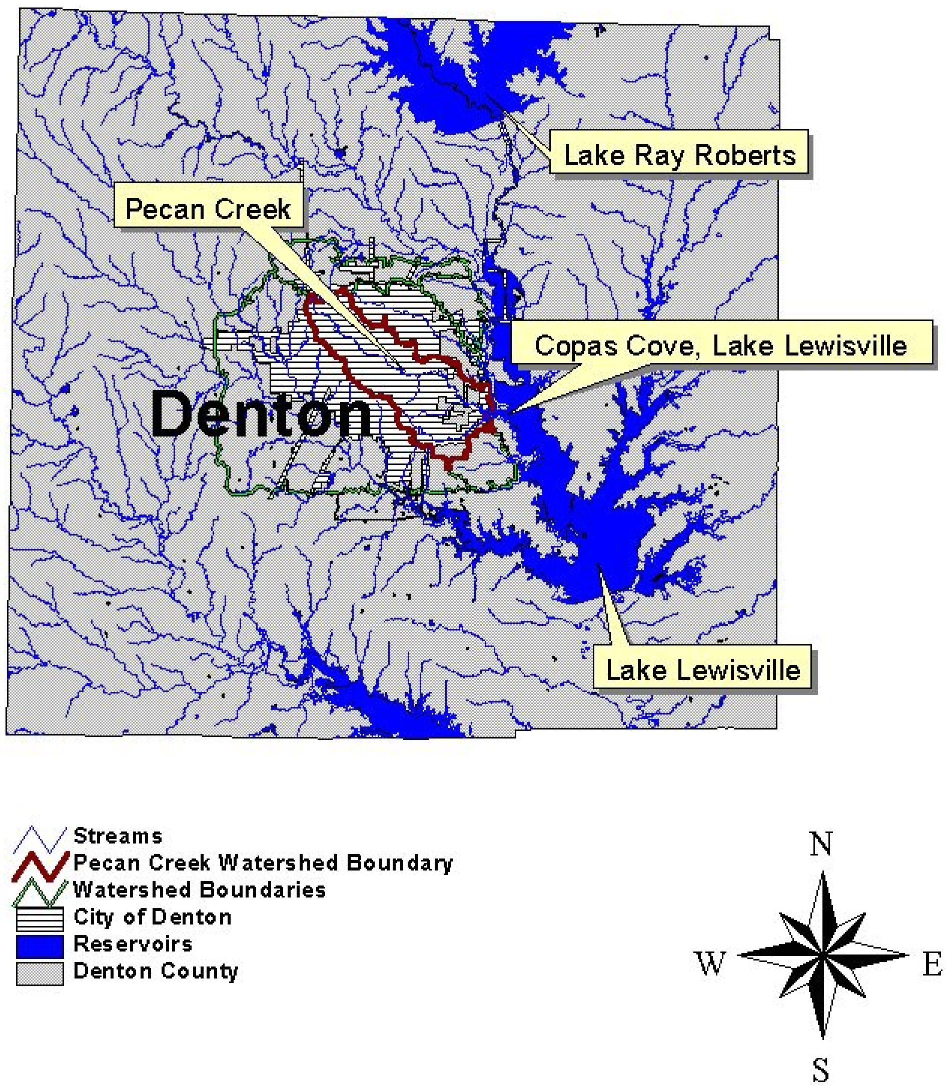

Figure 2.1 Location of Pecan Creek in Denton County, Texas.

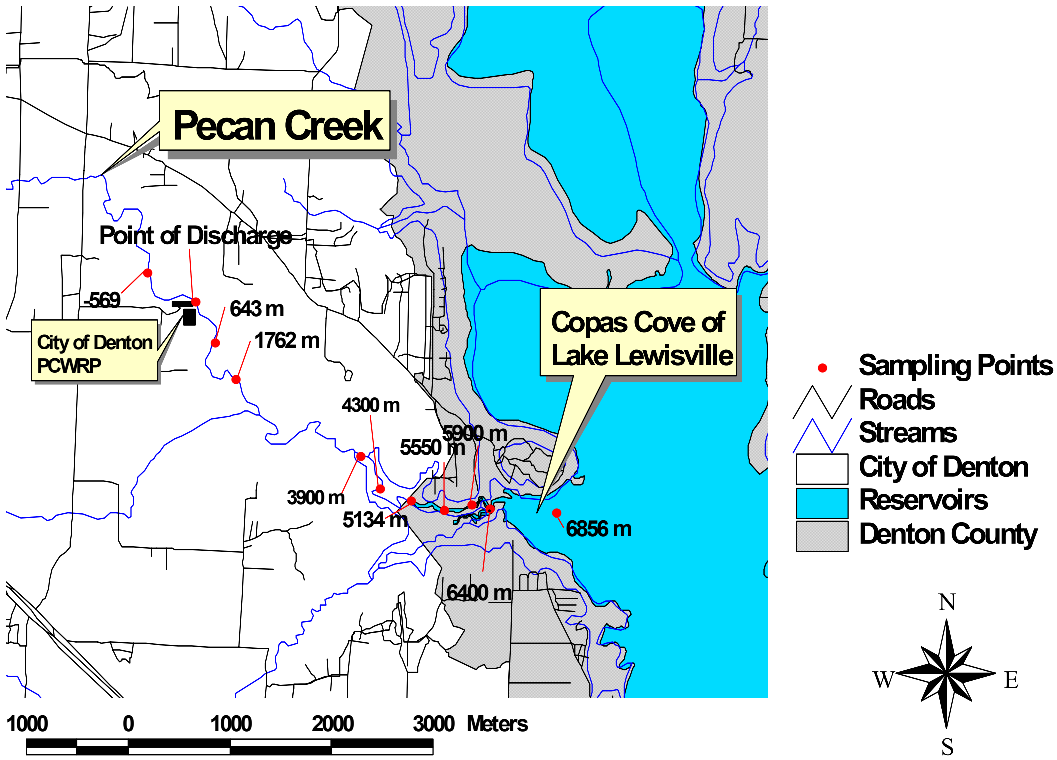

Figure 2.2 Location of the PCWRP and Pecan Creek monitoring stations.

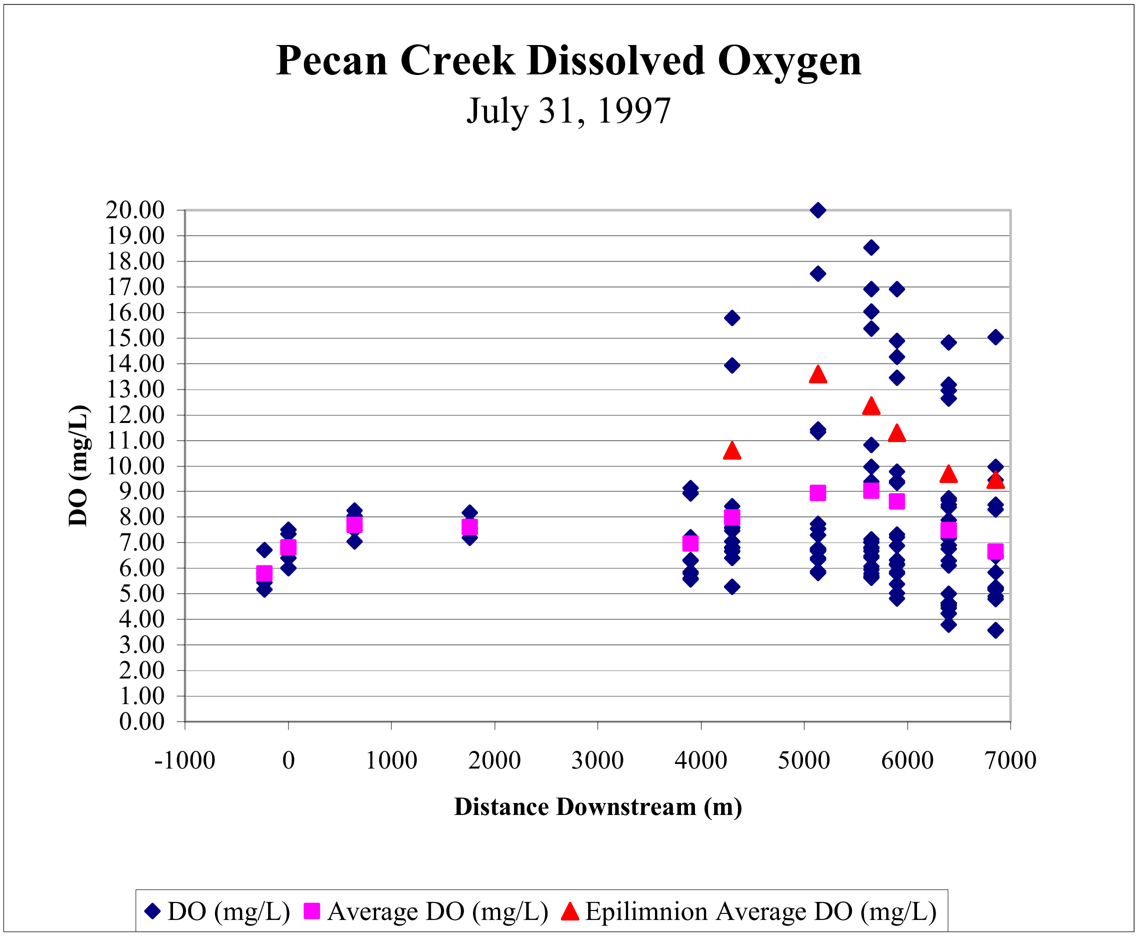

Figure 2.3 Pecan Creek DO (mg/L) July 31, 1997, -231 m upstream to 6,856 m downstream. PCWRP effluent discharge at 0 m.

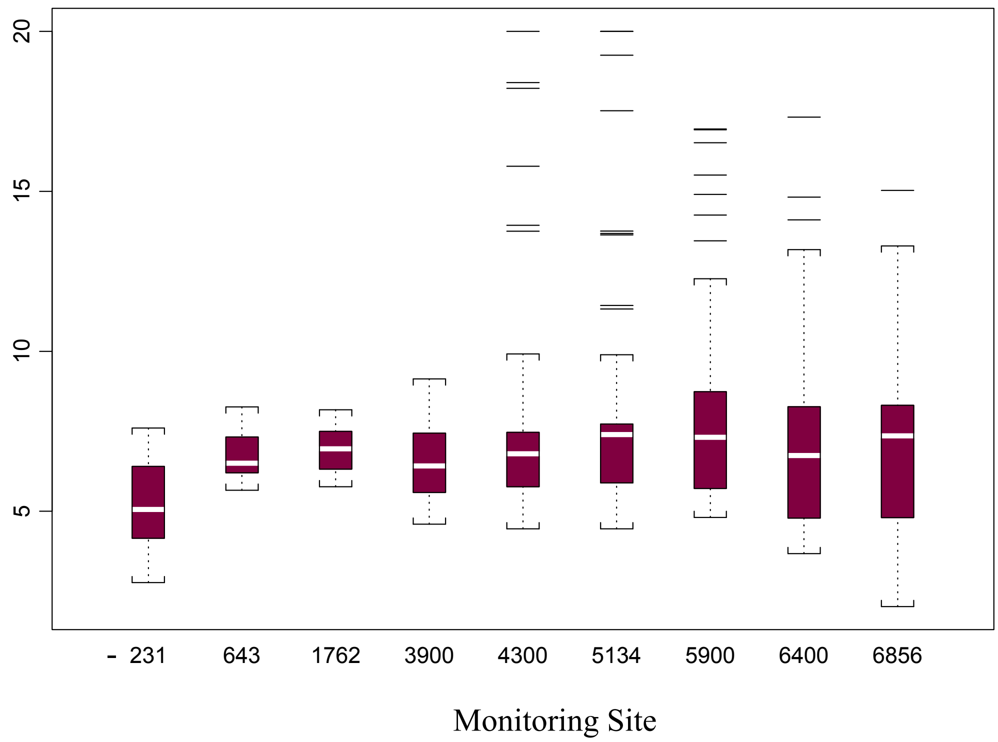

Figure 2.4 Boxplot of Summer 1997 Pecan Creek DO concentrations (mg/L) by Pecan Creek Monitoring Site. Boxplot results indicate the median value (white central bar), the interquartile distance (IQD) represented by the height of the box, extreme values of the data (1.5 x IQD) delineated by the whiskers, and outliers beyond the extremes (dashes).

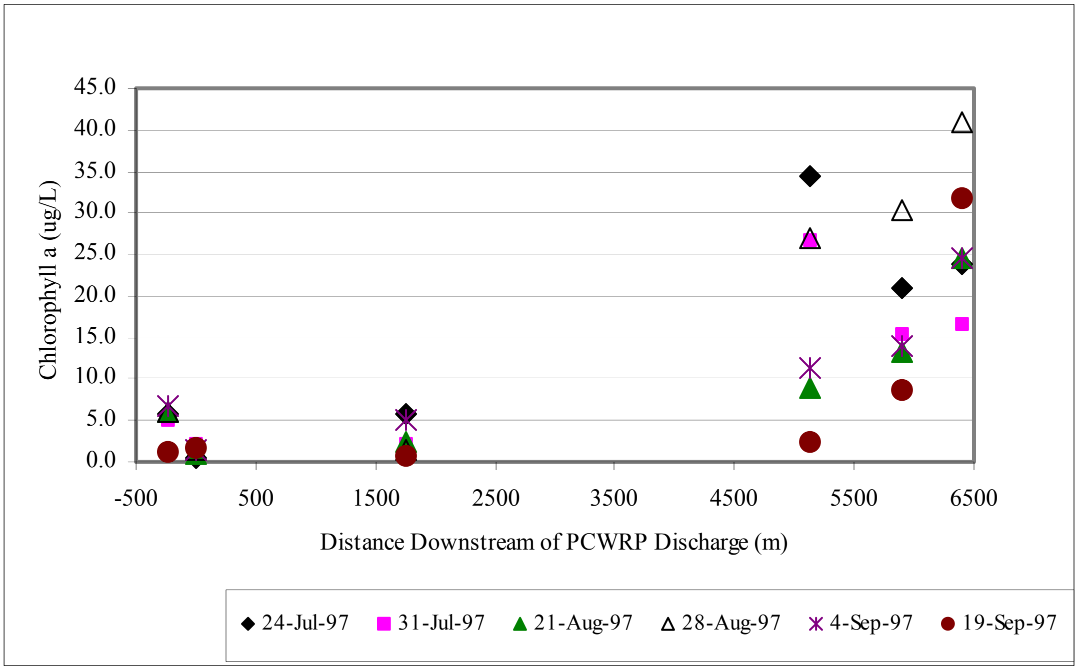

Figure 2.5 Average chlorophyll a concentrations for Pecan Creek, summer 1997.

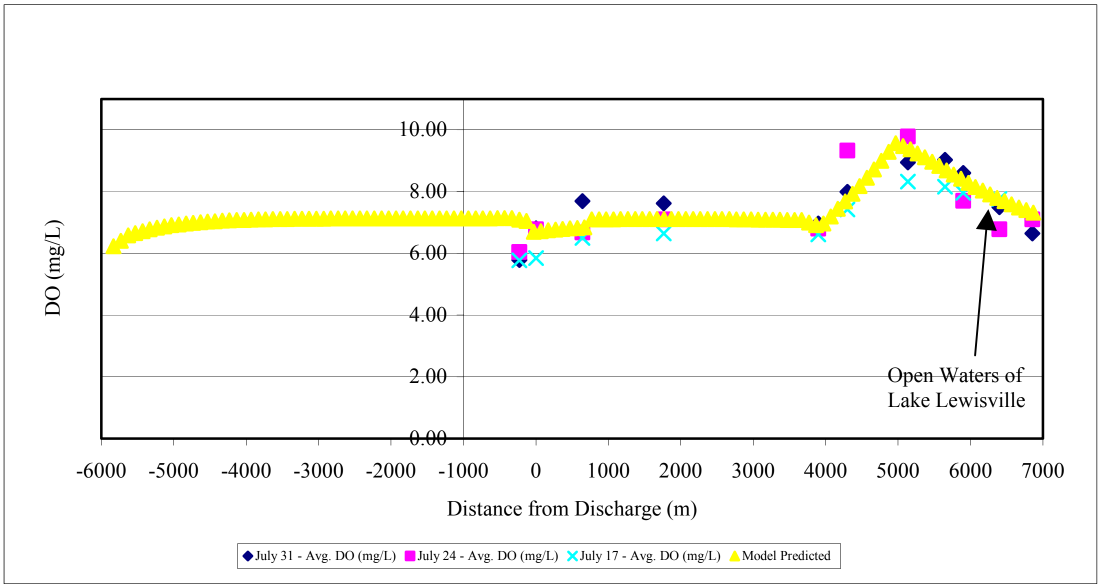

Figure 2.6 July 1997 data for average water column DO (mg/L) vs. QUAL2E predicted DO, calibration model set and evaluation sets. The Model Predicted DO is the model results for the July 31 – Avg. DO (mg/L) calibration data set. Calibration resulted in a 0.57% difference in actual vs. model projected DO at the critical point in the backwater area of Pecan Creek, at 3,900 m downstream.

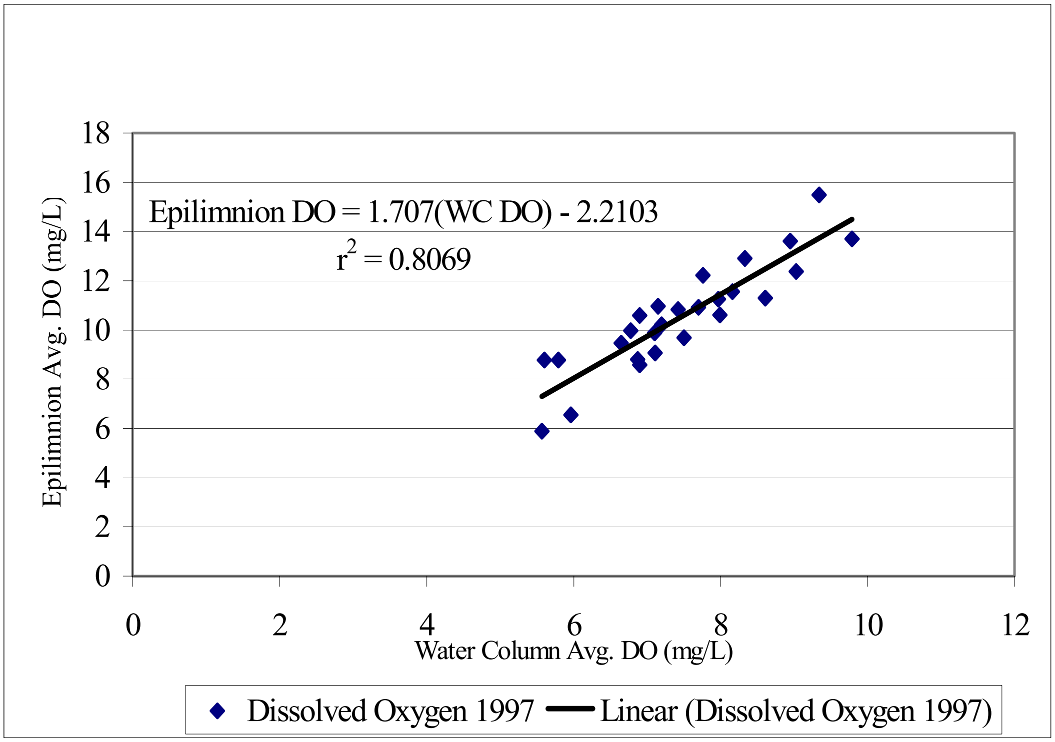

Figure 2.7 Linear regression analysis of water column and epilimnion dissolved oxygen for backwater areas of Pecan Creek.

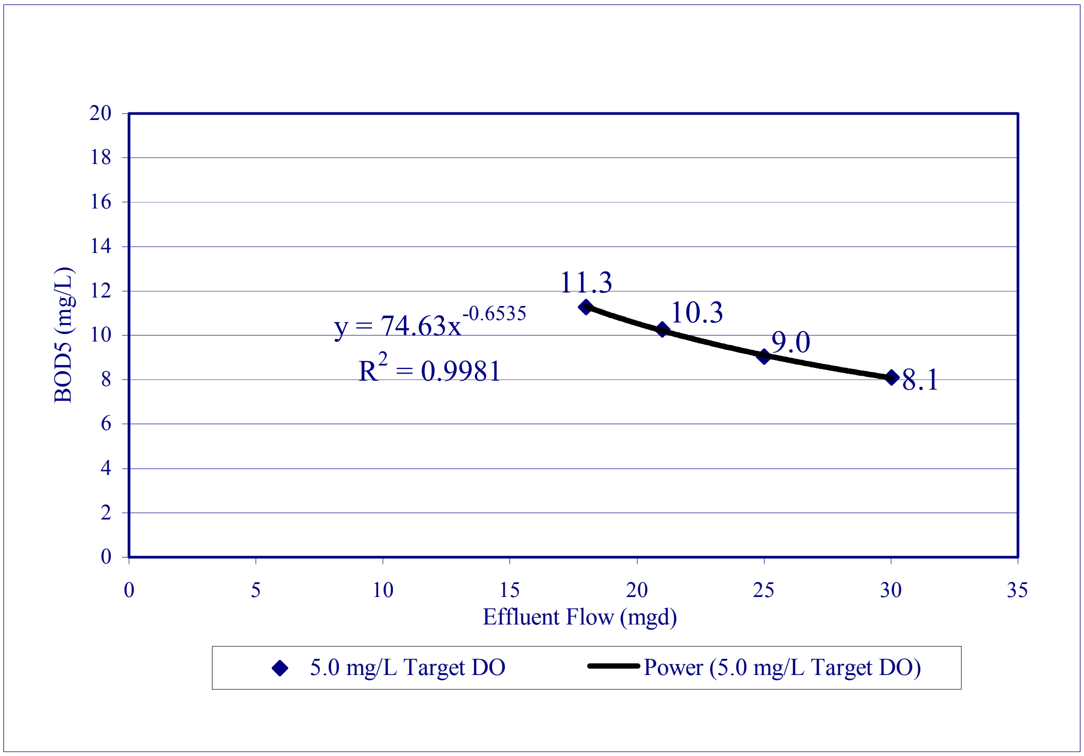

Figure 2.8 PCWRP BOD_5 WLA modeling results for the summer season for DO (mg/L) water quality standard attainment at an effluent NH_3-N of 2.0 mg/L.

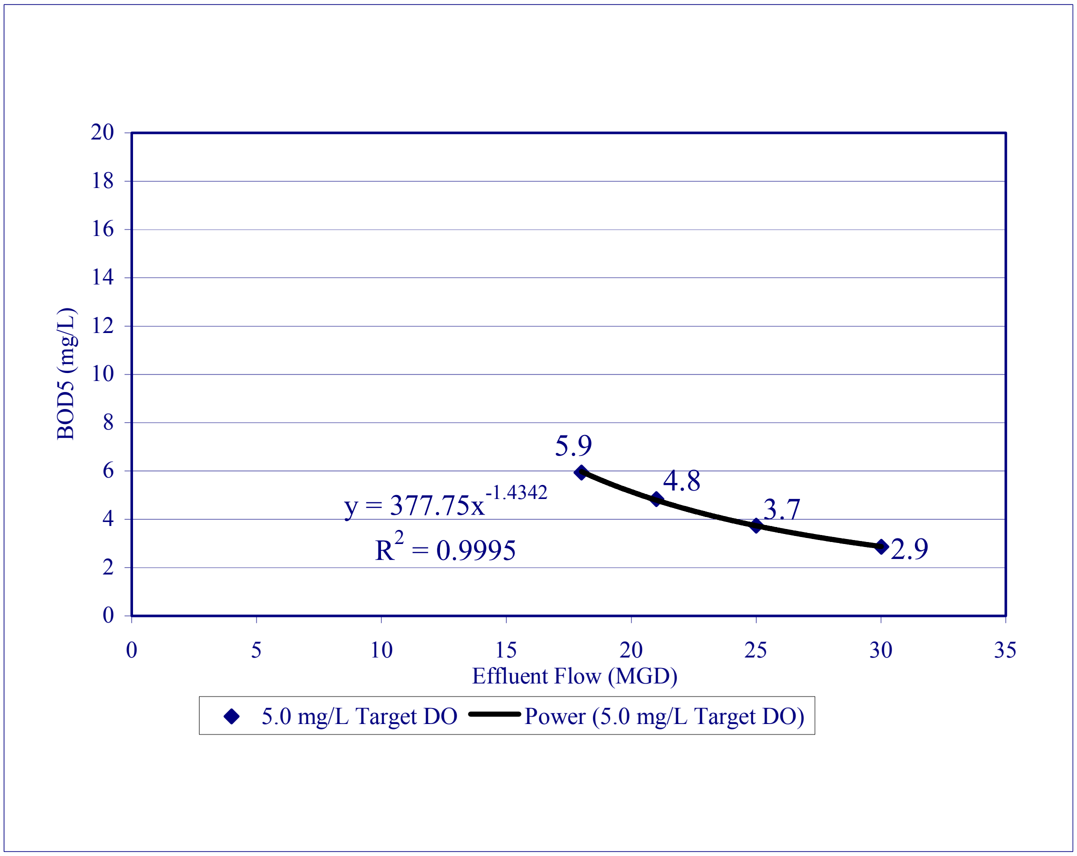

Figure 2.9 PCWRP BOD_5 WLA modeling results for the summer season for DO (mg/L) water quality standard attainment at an effluent NH_3-N of 3.0 mg/L.

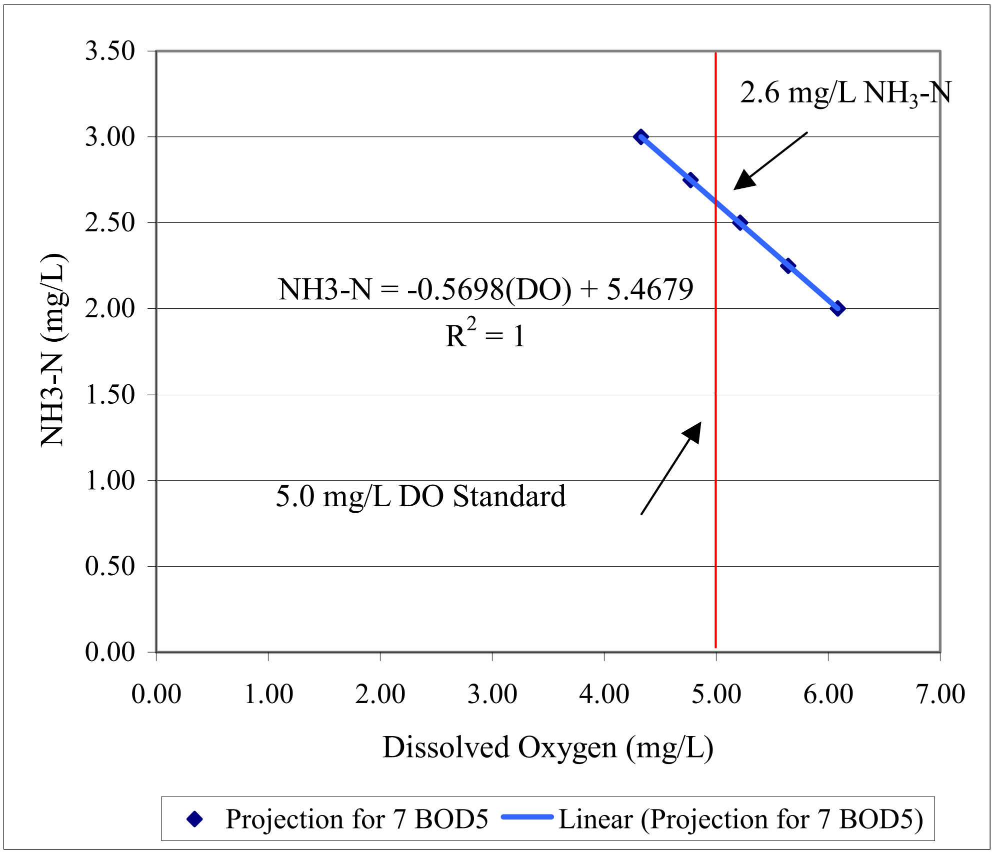

Figure 2.10 Linear regression of QUAL2E WLA model results for Pecan Creek critical sag point DO (mg/L) vs. PCWRP NH_3-N (mg/L) effluent concentration at 21 mgd effluent flow.

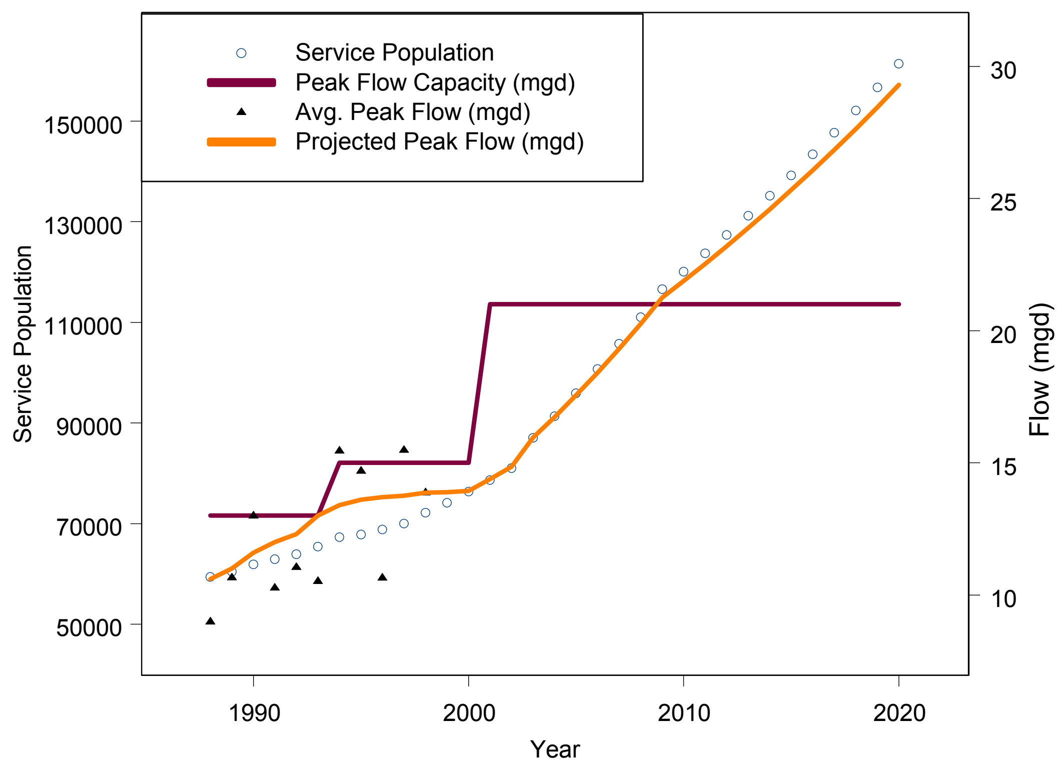

Figure 2.11 Denton wastewater service area analysis for PCWRP. Projected population growth in the service area through 2020 and expected wastewater flow capacity to meet demand.

CHAPTER 3

DISSOLVED OXYGEN TRENDS OF AN URBAN INTERMITTENT STREAM IN NORTH CENTRAL TEXAS RECEIVING A MUNICIPAL WASTEWATER EFFLUENT AND THEIR REGULATORY IMPLICATIONS

Introduction

Data for streams receiving effluent inputs and the resultant water quality characteristics was lacking in the past (Lung 1998). Streams that receive loadings from wastewater effluent can exhibit low dissolved oxygen, high nutrients, and changes in water chemistry (Lung 1998; USEPA 1999; Thomann and Mueller 1987). Although data for larger streams are available, data for intermittent or low flow streams are scarce. If these streams receive significant effluent flows what are the resulting spatial and temporal water quality trends?

This paper evaluates the water quality conditions in an intermittent urban stream, Pecan Creek, in North Texas that receives a municipal wastewater effluent. Results are presented that illustrate the water quality changes that can occur when such a stream becomes effluent dominated. Pecan Creek also provides a unique example of the water quality characteristics of an intermittent stream in an urban watershed that flows into the backwaters of a drinking water and recreational reservoir, Lake Lewisville.

Methods

Beginning in 1997 research was initiated to determine the water quality characteristics of Pecan Creek, Denton County, Texas. Pecan Creek is a tributary of the Elm Fork branch of the Trinity River. Focus of the study was determining the impact of the City of Denton's Pecan Creek Water Reclamation Plant (PCWRP) discharge on water quality resources of Pecan Creek and its associated backwaters in Lake Lewisville. Pecan Creek represents a situation that is becoming more common with the rapid urbanization of North Texas. An unfortunate fact is that data for effluent dominated low flow streams are lacking. Therefore, the assessment and characterization of water quality trends in these small urban stream systems is of timely importance. With the impairment of water quality of the nations waters being recognized as one of the greatest environmental threats to aquatic life and public health, the use of Total Maximum Daily Loads (TMDLs) to protect stream water quality is necessitated. However, adequate knowledge of water quality dynamics is needed to understand the use of TMDLs.

Study Area

Pecan Creek is located in Denton County, Texas (Figure 3.1). Comprising a watershed of approximately 63.5 km^2, Pecan Creek drains most of the City of Denton and eventually flows into Lake Lewisville. Land use in this watershed was 77% urban in 1997. Water quality monitoring and modeling efforts on Pecan Creek, Denton County, Texas, began in the summer of 1997 and ended in October of 2000. Study of Pecan Creek and the associated backwater cove of Lake Lewisville (Copas Cove) were initiated in response to the Texas Natural Resources Conservation Commission (TNRCC) review of Denton's National Pollutant Discharge Elimination System (NPDES) permit renewal application. The application was submitted for the PCWRP discharge to Pecan Creek, a discharge with permit limits for effluent flow, BOD_5, and NH_3-N. Discharge limits for these parameters are to provide for the attainment of specific waterbody uses and corresponding DO water quality standards in Pecan Creek and the backwaters of Lake

Lewisville pursuant to water quality regulation §307.7, Site-Specific Uses and Criteria (TNRCC 1997; TNRCC 1999).

Water Quality Monitoring

Water quality monitoring of Pecan Creek and the backwaters of Lake Lewisville (Copas Cove) was conducted to develop a database of water quality conditions. Although it was expected that PCWRP would have a major influence on water quality we wanted to confirm the resulting water quality trends and characteristics. Additionally, data collection was done to acquire data sets for water quality model development, calibration, and evaluation. Likewise, the surveys were used to assess the attainment of DO water quality standards for the advective and lentic portions of Pecan Creek.

Monitoring sites were located along Pecan Creek upstream from PCWRP and downstream to Copas Cove of Lake Lewisville (Figure 3.2). Although many of the sites monitored in 1997 were monitored in 1998, 1999, and 2000, sampling at several sites, in what was the backwater area of Pecan Creek, were abandoned beginning in 1998 due to inaccessibility. The waters of Lake Lewisville dropped approximately 7 feet by the summer of 1998, by more than 11 feet by the summer of 1999, and by about 15 feet by October of 2000 (Figure 3.3). Thus, many sites that were accessible by boat in 1997 could not be sampled in 1998 and 1999 due to the receding water. This change in the reduction of the backwater area resulted in the advective portion of Pecan Creek extending further and further downstream.

Diurnal water quality, DO, temperature, specific conductance, and pH, were monitored within hydraulically defined reaches and at specific locations in the Lake Lewisville region of Pecan Creek. Locations that were monitored in all years for water quality were the following distances upstream (-) or downstream (+) from the PCWRP discharge: Background (-231 m), PCWRP Effluent (0 m), Lotic Zone of Pecan Creek (+1,763 m), and the backwater areas of Pecan Creek (+5,134, +5,650, +5,900 m, +6,400 m, +6,856 m).

Additionally, other sites were monitored for DO to establish a more complete database for standard attainment and analysis. Water quality and diurnal monitoring events consisted of collecting *in situ* water quality parameters; DO (mg/L), temperature (°C), pH (s.u.), specific conductance (µs/cm), total dissolved solids (mg/L), and salinity (ppt). Each diurnal sampling event was conducted over an approximate 24-hour period. Water quality at each site was collected at up to three or four sampling times over the 24-hour period. Sampling consisted of taking measurements in a dawn to dusk pattern to establish the diurnal fluctuations in the parameters.

Water quality data were collected with a Hydrolab® Datasonde and Suveryor 4, water quality meter. The methodology for collecting samples varied between the upstream and downstream reaches, as conditions were distinct. In 1997, upstream Reaches1, 2, and 3, could be characterized as stream-like and lotic; however in 1998, 1999, and 2000 Reach 4, 5, and portions of Reach 6 became lotic. Sampling indicated that *in situ* water quality did not vary with depth in lotic reaches or laterally across the channel. Therefore all sampling in these reaches was conducted at available access points near the edge of water or in the case of the effluent at the final accessible point prior to discharge. All samples collected in the upstream reaches were taken near the surface of the available water column, by submerging the water quality probe below the surface.

Sampling in the Lake, Reaches 4, 5, and 6 in 1997, varied in that the water quality parameters were collected throughout the water column and lentic conditions were prevalent. Of course, this was the case for 1997, but changed during 1998, 1999, and 2000. It should be noted, that as drought conditions prevailed during the sampling season much of the backwater area became lotic and maximum depth decreased significantly. In fact, by August of 1998 a clear and defined channel extended through much of Reach 6, as Lake Lewisville had drastically receded. Therefore, in lotic regions, sampling was relegated to the surface of the water column or approximately 0.3-m of depth.

All sampling in backwater areas was conducted with a Hydrolab® Datasonde and Surveyor 4 unit attached to a metered data cable. To sample at a station with depth greater than 0.5 m the Datasonde would be lowered to the bottom and the total depth (m) would be recorded. The meter would then be raised to the closest 0.5-m increment, above the bottom, and measurements taken. Sampling would then continue at each 0.5-m increment until a depth of 0.5 m below the surface was attained. Measurements were also taken at 0.3 m below the surface in accordance with standard TNRCC Lake monitoring protocol for 1998, 1999, and 2000. For instance, if the total depth were 3.4 m the initial sample would be collected at 3.0 m, then 2.5 m, 1.5 m, 0.5 m, and 0.3 m. Sampling depths were dependent upon total depth (m) with exception to sampling at 0.3 m and 0.5 m below the surface. At each station the location was marked, referenced geographically with a Global Positioning System (GPS), Magellan® Trailblazer, and sampling was performed at mid-channel.

Water Chemistry Monitoring

Water Chemistry parameters selected for monitoring related to characterizing the influence of the PCWRP discharge on water quality in the lotic and lentic portions of Pecan Creek. Samples for laboratory analyses were collected at five locations as shown in Figure 3.2 and for the following parameters: Chlorophyll *a*, BOD_5, NH_3, Nitrate-Nitrite, Dissolved Ortho Phosphorous, Total Phosphorous, Total Kedjhal Nitrogen, Total Organic Carbon, Total Suspended Solids, and Volatile Suspended Solids. Water chemistry samples were analyzed by the City of Denton Municipal Laboratory, with the exception of Chlorophyll *a*, according to routine methods(American Public Health Association, American Water Works Association, and Water Environment Federation 1992; USEPA 1983). Chlorophyll *a* samples were analyzed in the University of North Texas Limnology Laboratory by prescribed methods for fluorometric analysis (Turner Designs 1994; Welschmeyer 1994; Arar and Collins 1992).

Samples were collected as grab samples. Samples were collected approximately 0.3 m below the water surface at all stations. All samples were collected from the main body of flow in the stream areas or at mid-channel in the lentic areas of Pecan Creek.

Results

Pecan Creek is an intermittent stream that is surrounded by urban land uses as it flows through the City of Denton to Lake Lewisville. Prior to entering Lake Lewisville and approximately 6,400 m upstream from that point, depending on the stage of Lake Lewisville, Pecan Creek receives the effluent discharge of the Pecan Creek Water Reclamation Plant (PCWRP).

Upstream from the PCWRP discharge the stream is intermittent with measured flows ranging from 0.000 m^3/s to 0.404 m^3/s. Minimum stream flow was maintained at or above 0.002 m^3/s with the exception of no flow on September 23, 1999. During this time North Texas was in the midst of a drought. Flows in Pecan Creek showed a typical pattern of increases during the spring runoff period and reductions during summer and fall (Figure 3.4).

Effluent flow from January 1, 1997 to December 31, 2001 is shown in Figure 3.5. As compared to Pecan Creek stream flow, PCWRP effluent flow was typically about 90% of the total instream flow downstream from the PCWRP discharge. During periods of increased base flow in Pecan Creek, as measured during the study, the effluent represented at least 50% or more of the instream flow. These data indicate that the PCWRP effluent resulted in significant changes in flow regime as compared to the background stream conditions.

Although maintenance of flow can benefit instream uses (Gibb and Richards 1978), changes in flow regime due to effluent discharge can alter other physical and water quality parameters. For example, dissolved oxygen (DO) concentrations in the background reaches showed a range of values from about 1.5 mg/L to 14 mg/L. Comparatively, the impacts of the effluent were to increase flow, ameliorate seasonal changes in DO, as witnessed in the background, and reduce variability (Figure 3.6).

Temporal changes in DO water quality were witnessed in Pecan Creek. DO conditions upstream from the discharge (Figures 3.7 and 3.8) showed a definite increase with the onset of winter, as expected with reduced temperatures, and a decrease following the increase in stream temperatures. DO concentrations immediately downstream from the effluent discharge (Figure 3.9) showed an extended period of increases due to the influence of the effluent on flow and temperatures. At approximately August of each year the DO minima was realized in Pecan Creek just downstream from the effluent discharge.

DO changes in the backwater zone of Lake Lewisville showed that the drought influenced variability in concentrations. The critical area in the backwater zone during 1997 was at about 4,900 to 5,134 m downstream from the PCWRP discharge. However, with the decrease in Lake Lewisville water levels and the extension of the advective reach of Pecan Creek the variability in DO concentrations witnessed in 1997 was reduced in 1998 and 1999 (Figure 3.10). Likewise, the DO concentrations measured at 6,400 m downstream from the discharge reflected similar changes (Figure 3.11). With near normal pool conditions within Lake Lewisville in the summer of 1998 DO exhibited much greater variability than in the summer months of 1999 and 2000. These conditions illustrate the need for varied compliance points for instream DO with changes in water level and conditions. Currently, NPDES permits in Texas do not account for changing reservoir levels that are a common occurrence in North Central Texas. Therefore, language and methods should be developed in the water quality guidance of Texas for backwater areas of reservoirs that receive effluents.

Discussion

Water quality measurements indicated that DO was highly variable in the backwater zones of Pecan Creek through the summer of 1998. However, with the onset of the drought and the extension of advective conditions downstream in Pecan Creek the DO variability of DO concentrations was reduced, as would be expected. These data indicate that a single compliance point for the attainment of water quality conditions and the establishment of a contour below which reservoir DO criteria should be met is inadequate. Future DO water quality compliance in Pecan Creek should be related to the stage of the reservoir. This will require water quality standards to be specified for streams that takes into account the influence of drought and dry-weather on reservoir levels and backwater conditions.

Results from this case study of Pecan Creek in Denton, County of North Central Texas have regulatory implications for intermittent urban streams that receive a municipal effluent and then enter a reservoir. The following technical issues related to water quality trends should be addressed in assessing compliance with dissolved oxygen standards: (1) the point of instream compliance for dissolved oxygen standards should be based on the physical conditions and resulting water quality of the stream/reservoir system; (2) each stream/reservoir system should have a unique method for assessing dissolved oxygen standard attainment; (3) as in the case of Pecan Creek, a single regulatory dissolved oxygen standard, based on the full pool elevation of the reservoir, will not be adequate across all seasons or years; (4) data inadequacies may limit the ability to assess instream compliance; and, (5) effluent dischargers should be required to collect seasonal and yearly water quality data to address system variability and changes in the receiving body of water.

References

1. American Public Health Association, American Water Works Association, and Water Environment Federation. 1992. *Standard Methods for the Examination of Water and Wastewater*. 18 ed. 1015 Fifteenth Street, NW, Washington, D.C..

2. Arar, E. J. and G. B. Collins. 1992. "Method 455.0 In Vitro Determination of Chlorophyll a and Pheophytin a in Marine and Freshwater Phytoplankton by Fluorescence." *Methods for the Determination of Chemical Substances in Marine and Estuarine Environmental Samples*. EPA/600/R-92/121. Cincinnati, OH: USEPA, Environmental Monitoring Systems Laboratory, Office of Research and Development.

3. Gibb, O. and H.J. Richards. 1978. "Planning for Development of Groundwater and Surface Water Resources." *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 363(1712):109-30.

4. Lung, W. S. 1998. "Trends in BOD/DO Modeling for Wasteload Allocations." *Journal of Environmental Engineering* (October):1004-7.

5. Thomann, R. V. and J. A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. New York, New York: HarperCollinsPublishers a gaging station (USGS).

6. TNRCC. 1997. "Chapter 307, Texas Water Quality Standards." Austin, Texas. §307.7. Site-Specific Uses and Criteria..

7. ———. 1999. *Methodology for Establishing Surface Water Quality Priorities for Texas River Basins*. Draft ed. Austin, Texas: TNRCC.

8. Turner Designs. 1994. *A Procedure for Measuring Extracted Chlorophyll a Free From the Errors Associated With Chlorophyll b and Pheopigments*. Sunneyvale, CA: Turner Designs.

9. USEPA. 1983. *Methods for Chemical Analysis of Water and Wastes*. Washington, D.C.: USEPA, Office of Research and Development.

10. USEPA. 1999. "TMDL Case Studies, #1-13" [Web Page]. Accessed 5 Oct 2000. Available at http://www.epa.gov/OWOW/tmdl/case.html.
Web site for the description of TMDLs and Studies.

11. Welschmeyer, N. A. 1994. "Fluorometric Analysis of Chlorophyll a in the Presence of Chlorophyll b and Pheopigments." *Limnology and Oceanagraphy* 39(8):1985-92.

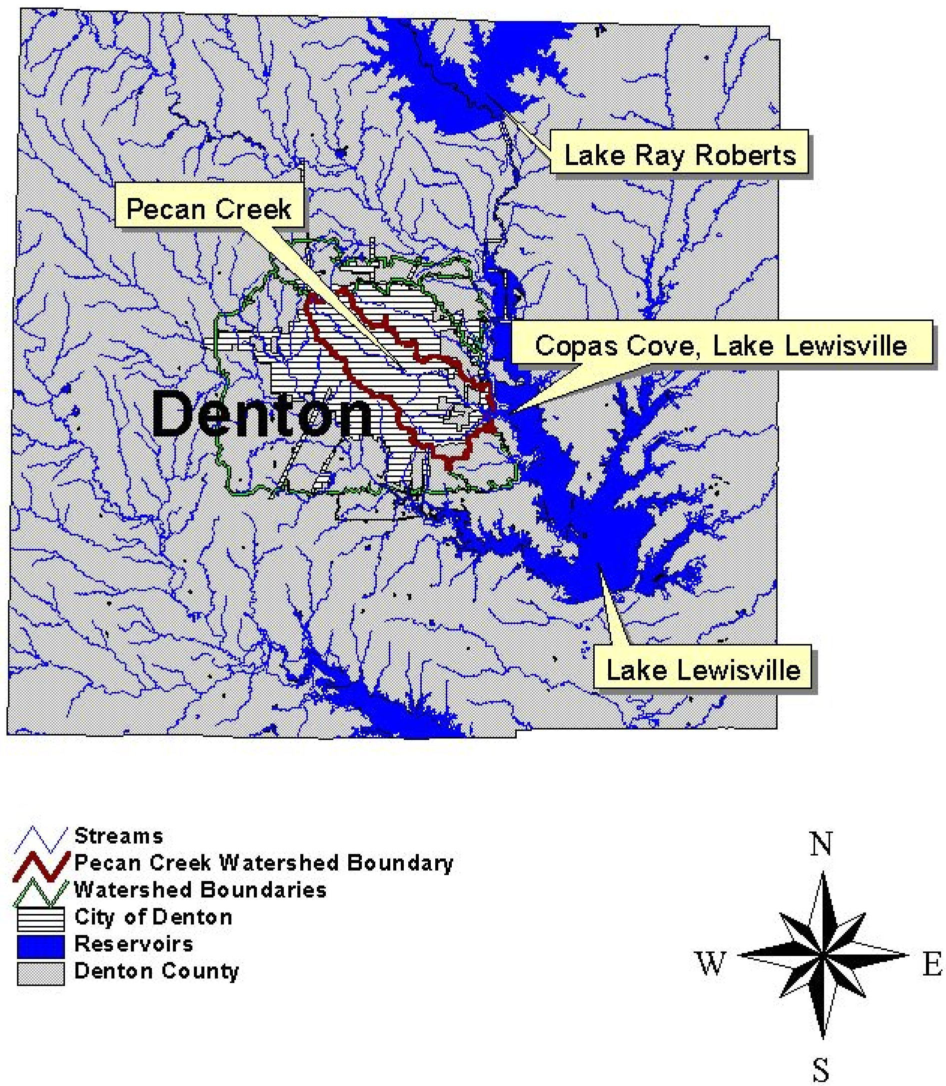

Figure 3.1 Location of Pecan Creek in Denton County of North Central Texas.

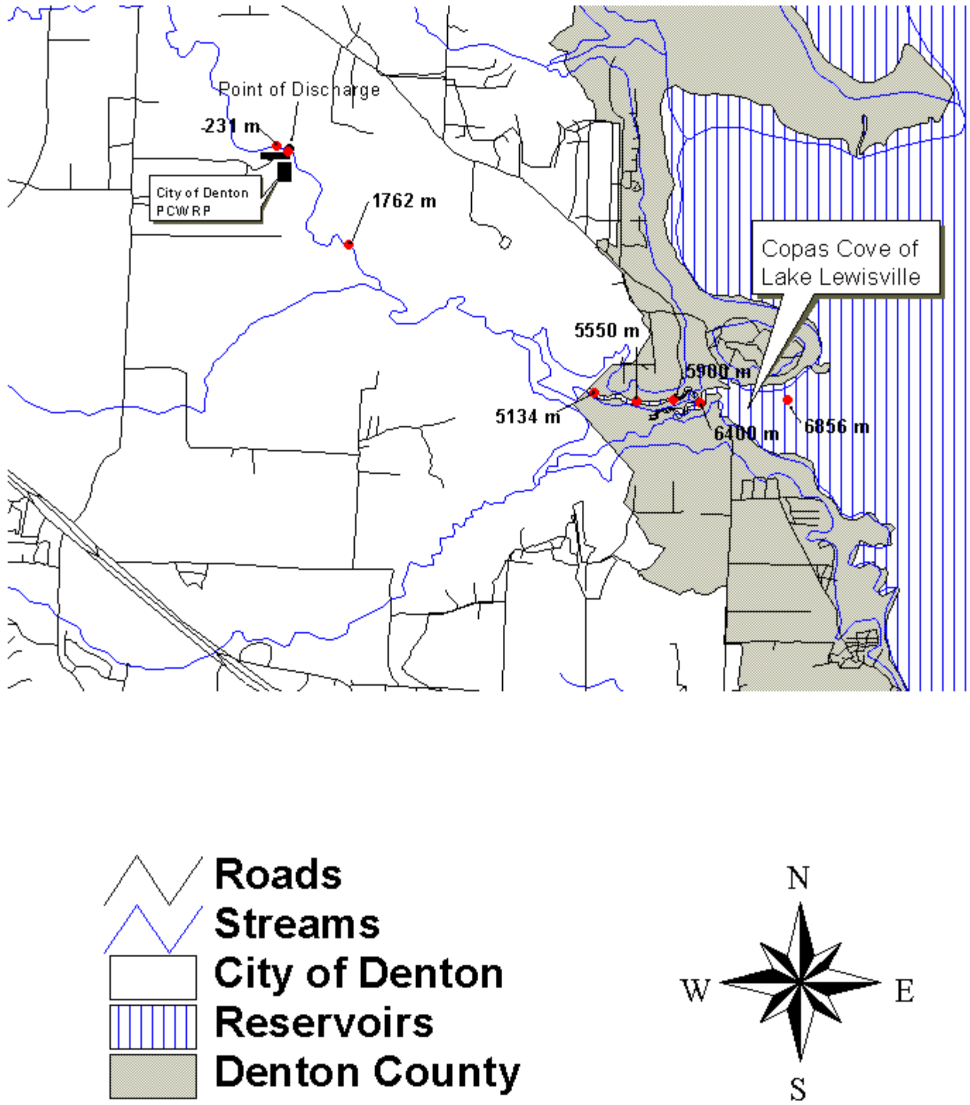

Figure 3.2 Pecan Creek monitoring stations.

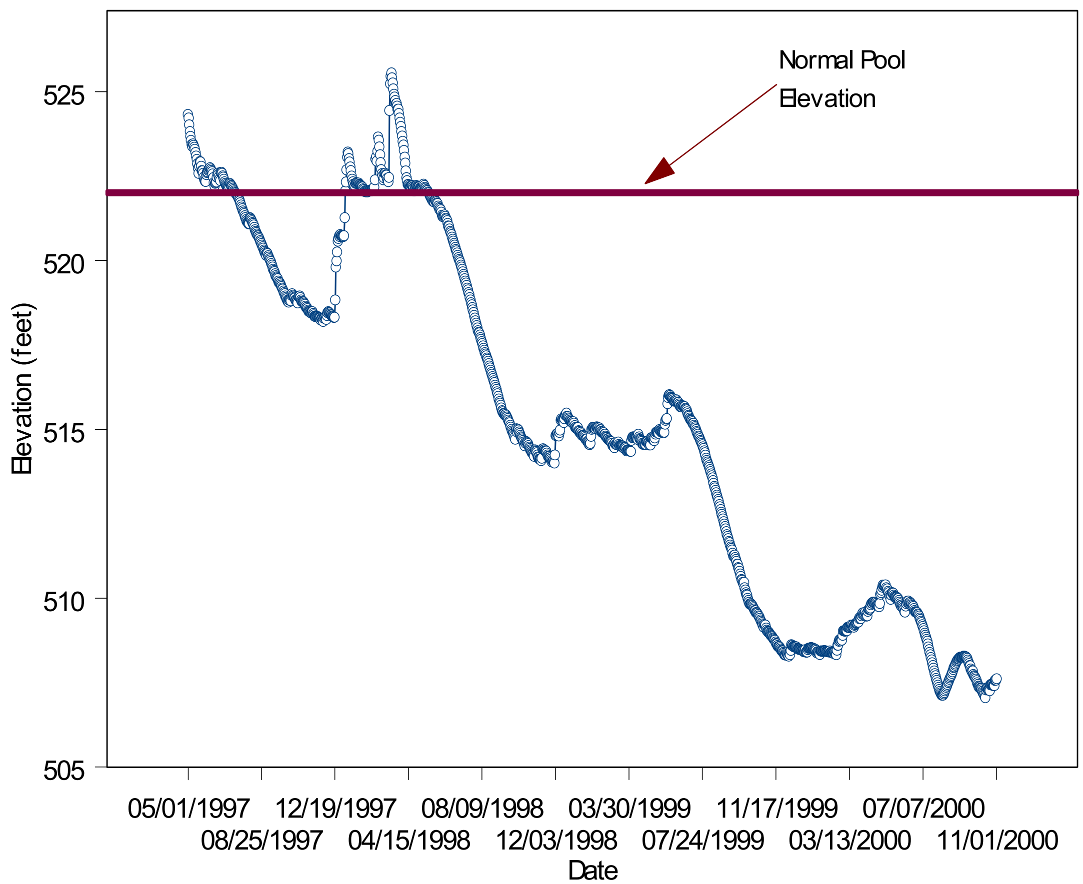

Figure 3.3 Lake Lewisville pool elevations during the period from May 1997 through October 2000. A reference line at 522 feet indicates normal pool elevation.

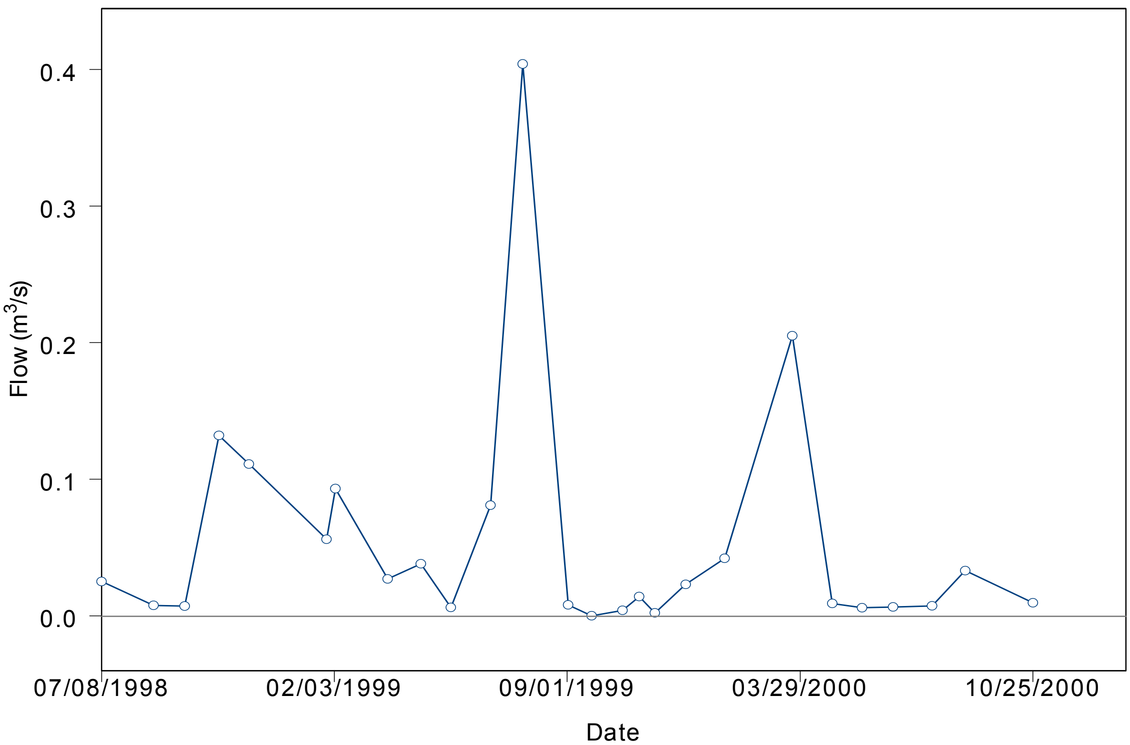

Figure 3.4 Measured base flow for Pecan Creek, Denton County, Texas.

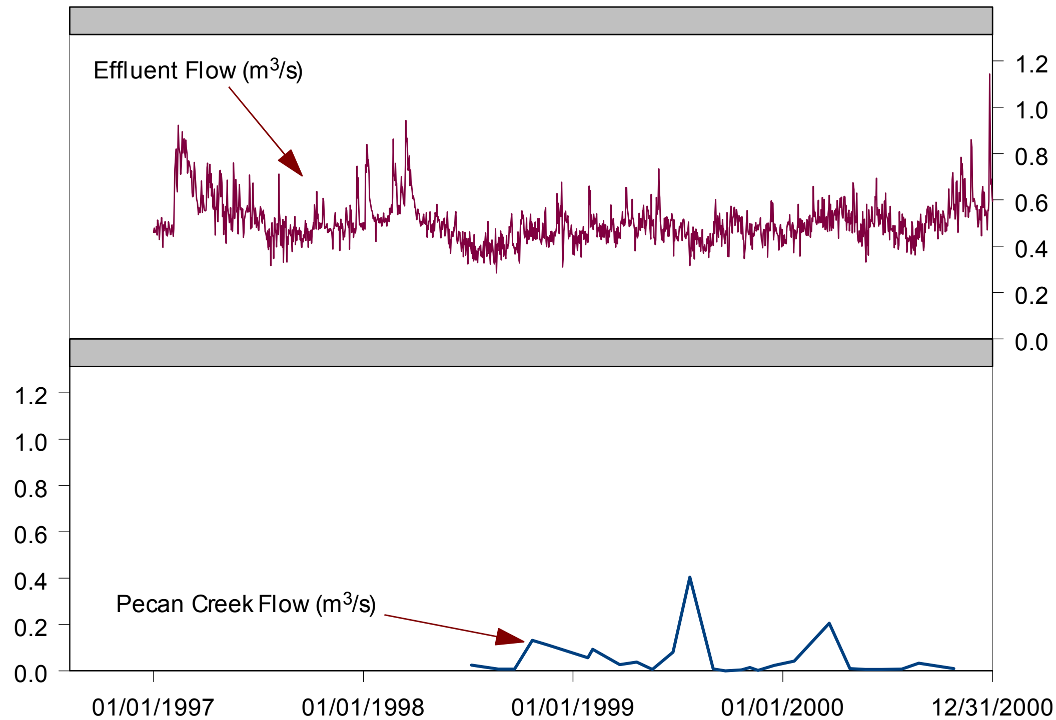

Figure 3.5 PCWRP effluent flow (m^3/s) and Pecan Creek stream flow (m^3/s).

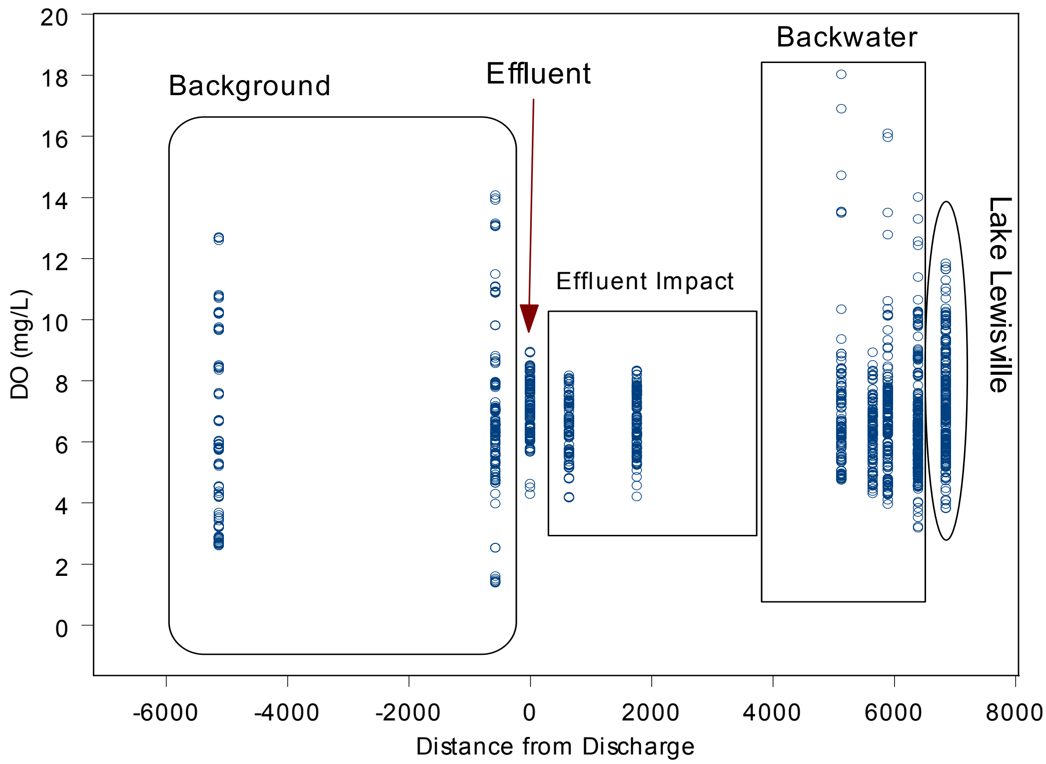

Figure 3.6 Dissolved Oxygen (mg/L) concentrations in Pecan Creek (April 1998 – October 2000)

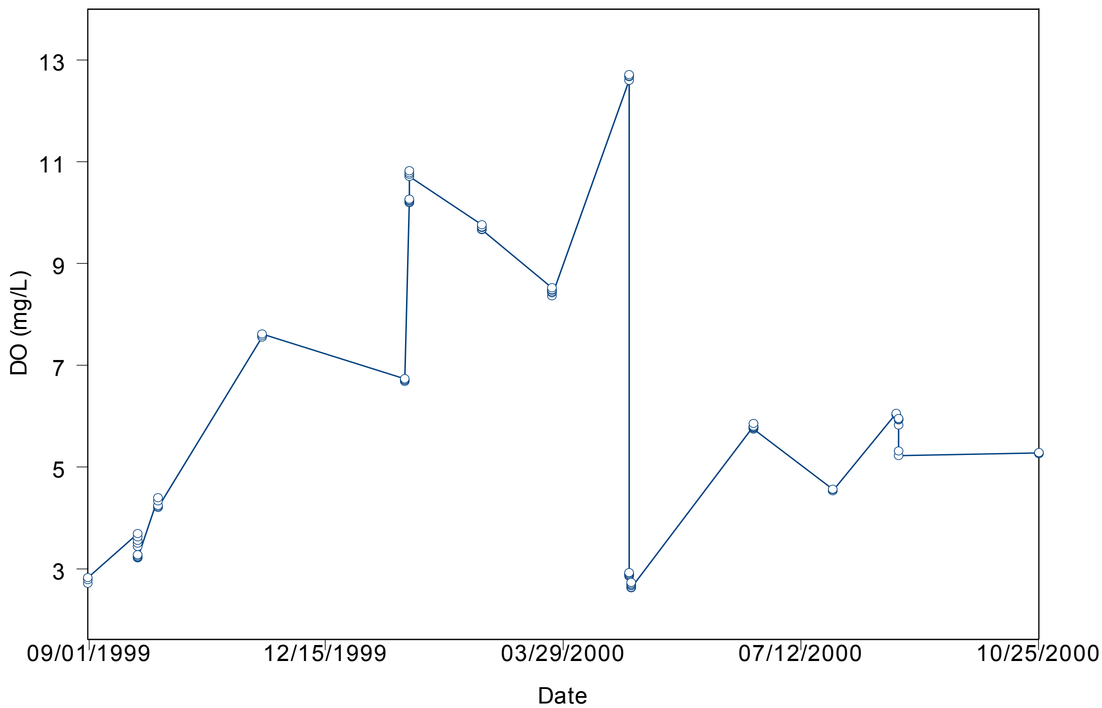

Figure 3.7 DO concentrations (mg/L) in Pecan Creek 5,126 m upstream from the PCWRP discharge. A spline plot function was used to assess temporal trends as represented by the line through the DO concentrations.

Figure 3.8 DO concentrations in Pecan Creek 569 m upstream from the PCWRP discharge. A spline plot function was used to assess temporal trends as represented by the line through the DO concentrations.

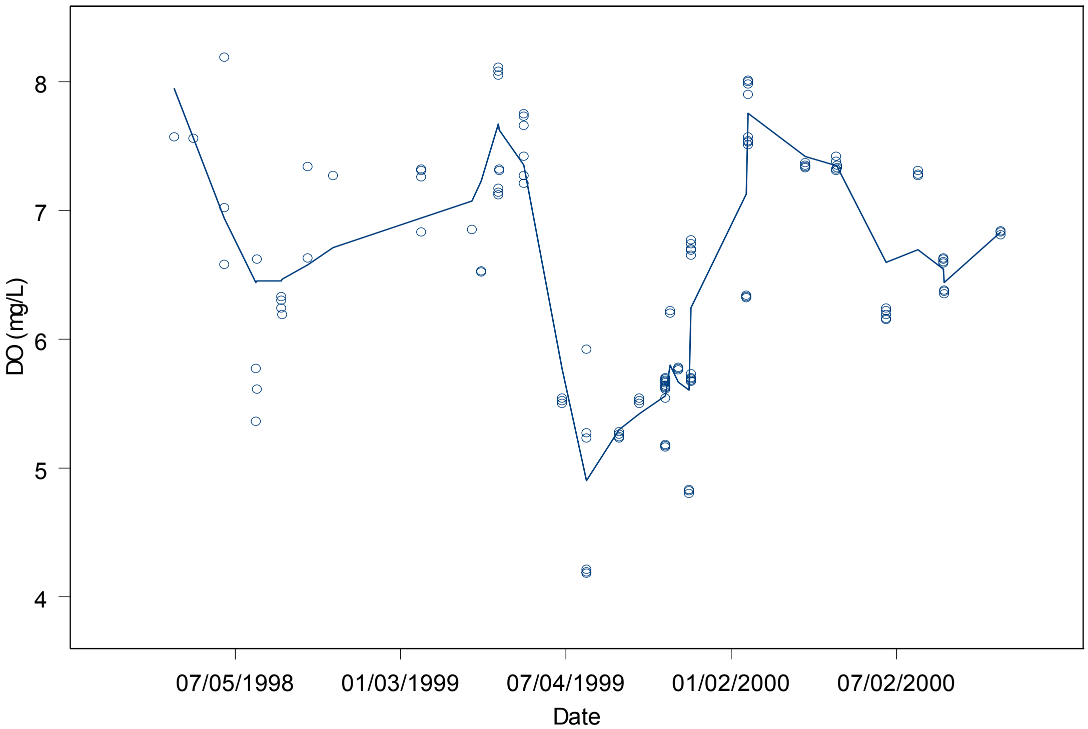

Figure 3.9 DO concentrations (mg/L) 643 m downstream from the PCWRP discharge. A spline plot function was used to assess temporal trends as represented by the line through the DO concentrations.

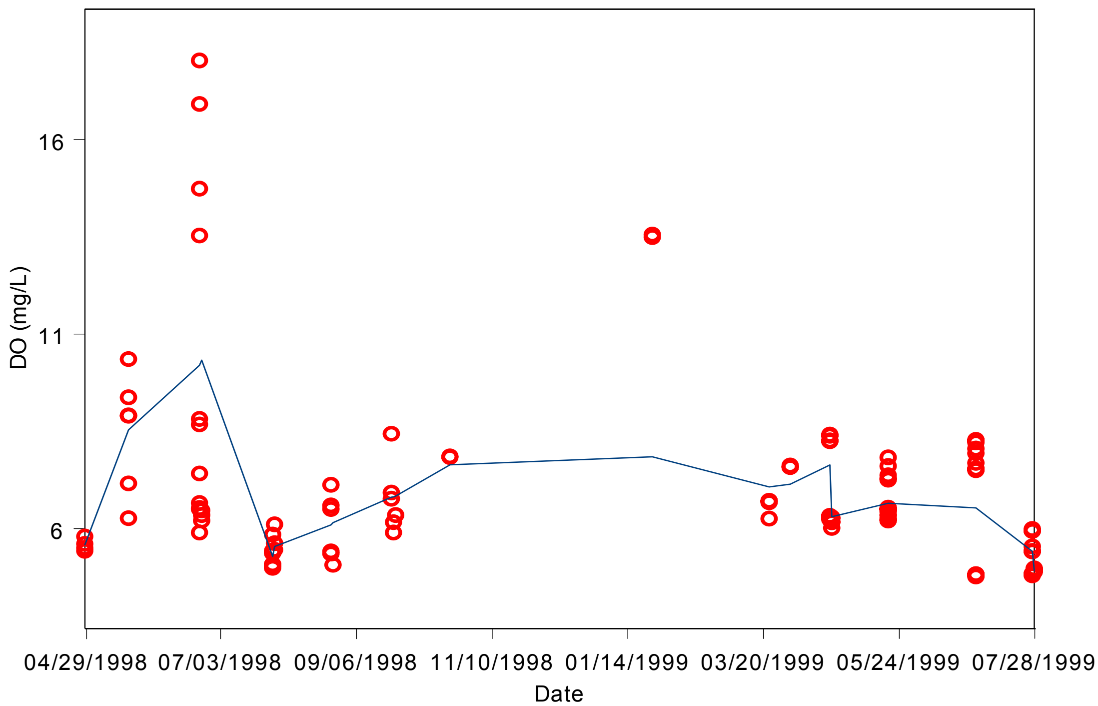

Figure 3.10 DO concentrations (mg/L) in Pecan Creek at 5,134 m downstream from the discharge (backwater zone). A spline plot function was used to assess temporal trends as represented by the line through the DO concentrations.

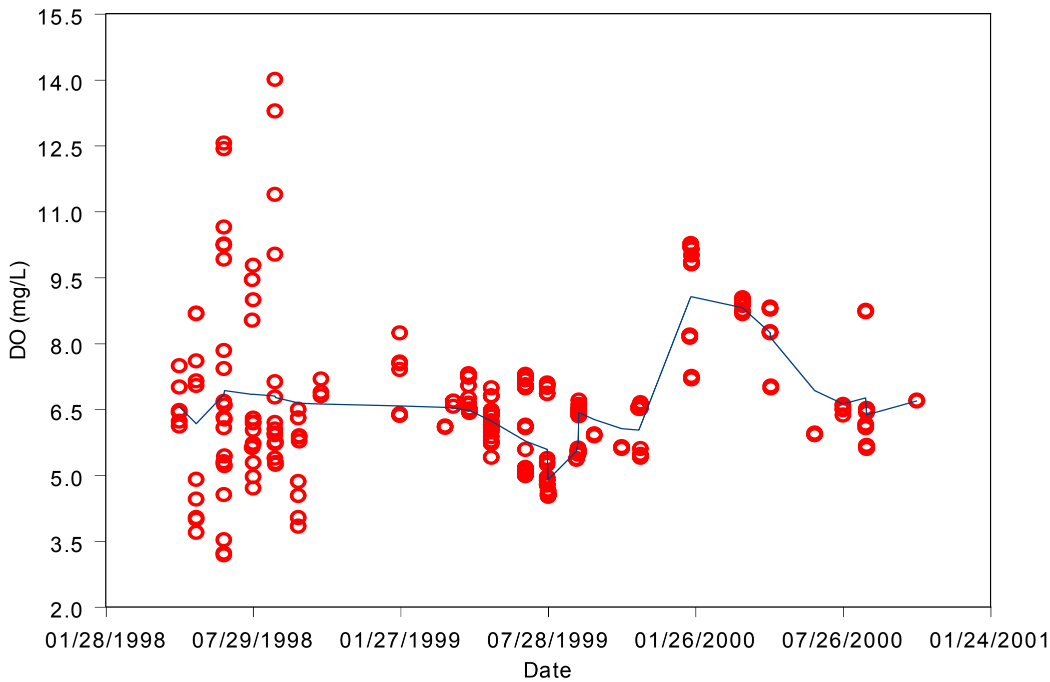

Figure 3.11 DO concentrations (mg/L) in Pecan Creek at 6,400 m downstream from the PCWRP discharge. A spline plot function was used to assess temporal trends as represented by the line through the DO concentrations.

CHAPTER 4

IMPACTS OF A SHORT-TERM DROUGHT ON WATER QUALITY OF A STREAM BACKWATER IN A NORTH CENTRAL TEXAS URBAN WATERSHED AND IMPLICATIONS FOR WATER RECLAMATION PLANT NPDES COMPLIANCE

Introduction

Beginning in 1996 and terminating in 2000 periods of drought were experienced throughout much of Texas. In North Central Texas the drought was characterized by increased public concern over reduced reservoir levels, including decreased recreational use and access. The drought, combined with anthropogenic water use, put a greater toll on reducing available water supplies, which produced widespread drinking water use restrictions.

Climate data for the City of Denton, Texas, the focal area for this study, illustrated that below normal precipitation had occurred in the North Central Texas region for the years of 1995, 1996, 1998, 1999, and 2000. Specifically, a continuous period of below normal rainfall was experienced in the Denton, Texas area from 1998 through 2000 (Figure 4.1). Precipitation was recorded at the lowest annual level in Denton, Texas since 1980 at 28.07 inches in 1999 (National Weather Service, Ft. Worth/Dallas 2001).

Implications of drought have been documented to include environmental impacts to watersheds, water quality impairments, reduced capacities of water storage reservoirs, alterations of biogeochemical cycling, and changes in biotic communities (Cao 2000;

Gibb and Richards 1978; Hoese 1960). Although drought may cause these environmental effects, drought is a normal part of the hydrological cycle. In the most basic terms, drought is a departure from normal levels of rainfall that results in drier than normal conditions (Gibb and Richards 1978). In the case of North Central Texas, drought conditions can occur over one season or a more extended period of time. Therefore, severity, duration, and the effects of the event characterize drought. Typically, droughts begin and end with a distinct pattern of lower than normal precipitation, followed by soil moisture loss, and materializing as decreased stream flows, falling reservoir levels, and reduced groundwater levels. (National Drought Mitigation Center 1995; Texas Water Development Board 2001).

Statewide droughts occurred throughout Texas in 1996 and 1998. These periods of drought produced environmental conditions that could be categorized as significant. The significance of the drought events in the late 1990's was witnessed as more than 300 cities and utilities implemented water management or restrictions (Texas Water Development Board 2001). The implications of these droughts were not alleviated in North Central Texas until the winter months of 2000-2001, when reservoir levels returned to normal. In the North Central Texas region near Denton, the surface elevation of Lake Lewisville had dropped by about 15 feet below the normal pool elevation of 522 feet above mean sea level by October of 2000.

This paper is based on a case study of an urban watershed in Denton, Texas (Figure 4.2). Pecan Creek watershed drains 63.5 km^2 that includes much of the developed area of Denton. A 3rd order stream, Pecan Creek receives effluent discharges from two point sources, nonpoint source runoff from the City of Denton Texas, and flows into Lake Lewisville. In 1998 one of the point sources was eliminated and only the City of Denton Water Reclamation Plant (WRP) discharged to the stream (Atkinson et al. 1997). With Pecan Creek being an intermittent stream, the City of Denton WRP discharge typically represented as much as 90% of the instream flow or more, with a permitted discharge of 15 MGD. Therefore, Pecan Creek had several rather distinct zones; an upstream zone with no influences from point source discharges, a free flowing zone that received point source discharges, and a backwater zone at the interface with Lake Lewisville in Denton County, Texas.

Research to assess the impact of drought on water quality of urban streams, specifically Dissolved Oxygen (DO) resources, is limited. This case study provides an assessment of an effluent dominated urban stream and the implications of drought on DO standard attainment as related to National Discharge Pollutant System (NPDES) permit conditions for a municipal WRP. The purpose of this research was to examine the influence of a short-term drought on water quality in Pecan Creek and assess the implications on water quality standard attainment by comparing a summer season of no drought in 1997 with a short-term period of drought over three summer seasons, 1998 through 2000. A method for determining the zone of compliance in streams that discharge to reservoirs and experience changing conditions due to fluctuating reservoir levels was assessed.

Methods

Beginning in 1997 research was initiated to determine the water quality characteristics of Pecan Creek, Denton County, Texas. Measurements were made to characterize the water quality conditions of Pecan Creek. Local goals of this research were to assess attainment of DO water quality standards in the stream (3.0 mg/L) and at the stream/reservoir interface (5.0 mg/L). During the period of assessment, from the summer of 1997 and through the fall of 2000, a short-term period of drought occurred. This phenomenon presented the opportunity to assess water quality trends as influenced by drought conditions and assess water quality changes with changes in the backwater region of the stream. Research also provided an opportunity to assess the NPDES permit conditions for the municipal wastewater treatment plant, Pecan Creek Water Reclamation Plant (PCWRP), and the Texas Natural Resource Conservation Commission standard permitting technique for streams discharging to a reservoir. The standard NPDES condition for streams in Texas that discharge to reservoirs is that reservoir DO water quality standards be met in the stream at the full pool elevation of the reservoir. In other words, if the full pool elevation is 522 feet above mean sea level, then DO is to be measured in the stream at the location where the stream intersects the 522-foot contour.

Water quality monitoring was accomplished monthly in the summers (May through September) of 1997, 1998,1999, and 2000. Monitoring of Pecan Creek and the backwaters of Lake Lewisville (Copas Cove) was conducted to develop a database of DO water quality conditions. The water quality surveys were used to assess the attainment of DO water quality standards for the advective and lentic portions of Pecan Creek. Table 4.1 shows the water quality criteria for Pecan Creek (TNRCC 1997a).

Table 4.1 Pecan Creek DO standards

Waterbody - Aquatic Life Use Sub-Category	DO Criteria Mean/Min (mg/L)	DO Criteria in Spring Mean/Min (mg/L)
Pecan Creek Arm of Lake Lewisville – High	5.0/3.0 (epilimnion avg.)	5.5/4.5 (epilimnion avg.)
Pecan Creek - Limited	3.0/2.0	4.0/3.0

Attainment of DO water quality and NPDES permitting for the City of Denton WRP, as specified by TNRCC, was based on meeting a 5.0 mg/L reservoir DO standard at the point where Pecan Creek intersected the 522 feet contour interval. This is the full pool elevation of the reservoir and was thought to represent the critical point for standard attainment, as the effluent loadings would cause the maximum DO depletion in backwater areas. Measurement of attainment was stipulated to be made at a Lake elevation of 522 feet above mean sea level. Therefore, upstream from the 522 feet elevation TNRCC considers the advective portion of Pecan Creek to occur and below is considered the impounded section of Pecan Creek or the Pecan Creek Arm of Lake Lewisville.

Monitoring sites were located along Pecan Creek upstream from the WRP and downstream to Copas Cove of Lake Lewisville (Figure 4.3). The effects of the drought were receding Lake Lewisville water levels and reduced stream flows. By the summer of 1998 Lake Lewisville dropped by about 7 feet and by more than 11 feet by the summer of 1999 (Figure 4.4).

Diurnal DO water quality was monitored within hydraulically defined reaches and at specific locations in the Lake Lewisville region of Pecan Creek. These locations were

5,134 m, 5,550 m, 5,900 m, 6,400m, and 6,856 m downstream from the PCWRP effluent discharge. Locations that were monitored in all years for water quality were the following distances upstream (-) or downstream (+) from the PCWRP discharge: Background (-231 m), PCWRP Effluent (0 m), Lotic Zone of Pecan Creek (+1,763 m), and the backwater areas of Pecan Creek (+5,134, +5,650, +5,900 m, +6,400 m, +6,856 m).

DO water quality data was collected with a Hydrolab® Datasonde and Suveryor 4, water quality meter. The methodology for collecting samples varied between the upstream and downstream reaches, as conditions were distinct. In 1997, upper reaches of Pecan Creek could be characterized as stream-like and lotic, except in 1998 and 1999 when lower reaches of the stream became lotic. Sampling indicated that *in situ* water quality did not vary with depth in lotic reaches or laterally across the channel. Therefore, all sampling in these reaches was conducted at available access points near the edge of water or in the case of the effluent at the final accessible point prior to discharge. All samples collected in the upstream reaches were taken just below the surface of the available water column, by submerging the water quality probe below the surface. Each sampling day the water quality meter was calibrated for DO, pH, and specific conductance (American Public Health Association, American Water Works Association, and Water Environment Federation 1992).

Sampling in the lentic reaches of Pecan Creek in 1997 consisted of collecting water quality parameters throughout the water column, at 0.5 m intervals. Of course, this was the case for 1997, but changed during 1998 and 1999. It should be noted, that as drought conditions prevailed during the sampling season much of the backwater area became lotic and maximum depth decreased significantly. In fact, by August of 1998 a clear and defined channel extended through much of the lower reaches of the stream, as Lake Lewisville had drastically receded. Therefore, in lotic regions, sampling was relegated to the surface of the water column or approximately 0.3 m of depth.

Water quality sampling in backwater areas for 1997 was conducted with a Hydrolab® Datasonde and Surveyor 4 unit attached to a metered data cable. To sample at a station the Datasonde would be lowered to the bottom and the total depth (m) would be recorded. The meter would then be raised to the closest 0.5-m increment above the bottom and measurements taken. Sampling would then continue at each 0.5-m increment until a depth of 0.5 m below the surface was attained.

Results

As shown in Figure 4.1, below normal monthly precipitation totals occurred in the Denton, Texas area from about April of 1998 through 2000. Corresponding to these precipitation totals, the pool elevation of Lake Lewisville (reservoir) receded through the fall of 2000. Total precipitation for 1999, 28.07 inches, was the lowest recorded since 1980 and well below the annual norm of 37.27 inches. Annual precipitation data for the period of 1980 through 2000 and 30-year annual norms are shown in Table 4.2.

Reductions in the surface elevation of the reservoir corresponded to changes in stream hydrology at the reservoir/stream interface. For example, during 1997 the advective reaches of the stream extended to about +4,900 m downstream from the PCWRP discharge. Whereas, by the summer of 2000 the advective reach extended to about +7,000 m downstream of the effluent discharge, as observed by velocity measurements and reduced stream depths.

Comparison of DO values for summer sampling events of 1997 through 2000 were done to assess the influence of the drought on minimum and maximum surface water DO conditions. For each measurement period or event a Diurnal Fluctuation Value (DFV) was calculated for a series of DO measurements as:

$$DO_{max} – DO_{min} = DFV$$

DFVs for specific sampling sites in the backwater region of Pecan Creek were then regressed against Lake Lewisville pool elevation data for the summer seasons of 1997, 1998, and 1999.

Linear regression and Spline plots were used to assess a fit of the data and to determine the point of lotic influence on DFV values. Additionally, Spline plots illustrated when critical stages occurred in the stream/reservoir interface that minimized DFVs. At the onset of lotic conditions and reduced DFVs the correlation of DFVs to pool elevation was reduced or nonexistent. Thus, the data sets were truncated, by visual inspection, at the point where the DFVs were not influenced by pool elevation prior to performing regression analysis (Figure 4.6).

A significant linear trend for summer DO concentrations, with dependence upon pool elevation (ft), was determined at each site with r^2 values of 0.78, 0.65, 0.76, 0.79 and 0.75, for +6,856 m, 6,400 m, 5,900 m, 5,650 m, and 5,134 m downstream, respectively (Figure 4.7). Results indicated that all stations in the backwater zone, at the stream/reservoir interface, exhibited relationships between DFV and Lake Lewisville pool elevation (ft), until lotic conditions prevailed at a site. Time under the influence of lentic conditions was reduced moving upstream toward the PCWRP effluent discharge.

Results of the regression analysis for upstream extent of lentic conditions, under pool elevation influence, versus the pool elevation are shown in Figure 4.8. The determination of critical distance downstream from the PCWRP effluent discharge, for assessment of DO standard attainment, can be made by using the predicted regression equation and the pool elevation of Lake Lewisville. The predictive regression equation is:

$$\text{Critical Distance} = 134{,}248 \text{ m} + (-249.29 \text{ m/ft} * \text{LL pool elev. (ft)})$$

Therefore, water quality data for Pecan Creek, during the drought conditions of 1997 through 2000, indicated that the pool elevation significantly alters lentic conditions that influence the DFV and result in the need to assess DO standard attainment at the most upstream point of lentic conditions. The predictive equation can be used to locate the critical zones to assess NPDES permit compliance for the PCWRP.

Discussion

Drought conditions that existed in 1997 through 2000 in North Central Texas resulted in reduced pool elevations and storage of water in Lake Lewisville, near Denton, Texas. Pecan Creek, which receives runoff from the city of Denton and effluent form PCWRP, the City of Denton's WRP, experienced changes in water quality due to the fluctuations in Lake Lewisville pool elevations. The greatest impact to water quality was the change in lentic conditions over time and with spatial extent in Pecan Creek.

Current NPDES permit conditions for PCWRP indicate that the DO compliance point for Pecan Creek is at the point where the stream intersects the normal pool elevation for Lake Lewisville of 522 ft. This point of compliance is at approximately 4,900 m to 5,134 m downstream from the effluent discharge, based on monitoring data

(Atkinson et al. 1997). However, results from this study show that the drought had a significant influence on the variability of DO conditions in Pecan Creek. Specifically, DFVs measured in Pecan Creek were greatest at all sites when lentic or backwater conditions were prevalent.

The data generated during this study indicates that future monitoring to assess the impact of the PCWRP effluent on the water quality of Pecan Creek should be done dependant upon the pool elevation of Lake Lewisville. Drought conditions do occur with regular intervals in the region and will continue to influence reservoir levels and storage. Therefore, these changes will require that monitoring be done in a manner to assess the greatest extent of impact on DO resources. Otherwise, the risk to the aquatic ecosystem of Pecan Creek and the backwaters of Lake Lewisville will be underestimated.

This research illustrates the need to assess backwater areas of streams that interface with reservoirs dependant upon the prevailing precipitation patterns. Although it was expected that DO variability would decrease with the onset of lotic conditions it was not expected that pool elevation could be used as a tool to predict critical zones for assessment of DO resources. This research further shows the need for municipalities, regulatory agencies, and those monitoring the influence of point sources and/or runoff to address the effects of drought conditions and the influence of reservoirs on the water quality of receiving stream backwaters. Future consideration should be made to correct current NPDES permit conditions for facilities in Texas and other states that discharge to reservoirs, via streams, to include a sliding spatial scale of compliance based on reservoir elevations.

Results suggest that stratified and eutrophic conditions of Pecan Creek backwaters are dependant upon the pool elevation. This is in accordance with DO measurements and illustrates the need for a variable point of compliance dependant upon the pool elevation and the effects of drought. Implications for operation of the PCWRP are that normal pool elevations in the reservoir may result in the most stringent conditions, as the waste stream has a reduced time of travel and impacts a more stratified body of water. Future operational parameters of the plant should be designed to allow for changing reservoir conditions. Additional treatment that reduces nutrient inputs may be a best management practice to minimize variability in diurnal DO.

References

1. American Public Health Association, American Water Works Association, and Water Environment Federation. 1992. *Standard Methods for the Examination of Water and Wastewater*. 18 ed. 1015 Fifteenth Street, NW, Washington, D.C..

2. Atkinson, S. F., K. L. Dickson, G. D. Maschmann, R. D. Taylor, J. Coulter, and G. Stover. 1997. *Water Quality Assessment of City of Denton's WWTP Effluent on Pecan Creek and Lake Lewisville*. Denton, Texas: University of North Texas.

3. Cao, H. 2000. "El Nino-La Nina Events, Precipitation, Flood-Drought Events, and Their Environmental Impacts in the Suwanne River Watershed, Florida." *Environmental Geosciences* 7(2):90-98.

4. Gibb, O. and H.J. Richards. 1978. "Planning for Development of Groundwater and Surface Water Resources." *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 363(1712):109-30.

5. Hoese, H. D. 1960. "Biotic Changes in a Bay Associated With the End of a Drought." *Limnology and Oceanography* 5(3):326-36.

6. National Drought Mitigation Center. 1995. "Understanding and Defining Drought" [Web Page]. Accessed 21 Nov 2001. Available at http://enso.unl.edu/ndmc/enigma/def2.htm.

7. National Weather Service, Ft. Worth/Dallas. 2001. "Normal, Means, and Extremes" [Web Page]. Accessed 21 Nov 2001. Available at http://www.srh.noaa.gov/fwd/CLIMO/coop/denton.html.

8. Texas Water Development Board. 2001. "The Drought in Perspective 1996 - 1998" [Web Page]. Accessed 21 Nov 2001. Available at http://www.twdb.state.tx.us/data/drought/DroughtinPerspective.htm.

9. TNRCC. 1997. "Chapter 307, Texas Water Quality Standards." Austin, Texas. §307.7. Site-Specific Uses and Criteria..

10. ———. 1999. *Methodology for Establishing Surface Water Quality Priorities for Texas River Basins*. Draft ed. Austin, Texas: TNRCC.

11. Trinity River Authority. 1998. *Quality Assurance Project Plan: Water Quality Assessment of City of Denton's PCWRP Effluent on Pecan Creek and Lake Lewisville*. QAPP PC1998.

Table 4.2 Precipitation totals at the City of Denton for the period of 1961 – 1990. Monthly precipitation totals are shown from the period of 1980 through 2000.

30 Year Normals (1971-2000)															
Month			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Normal	Maximum (°F)		53.3	59.2	67.2	74.4	81.7	89.2	94.1	93.5	86.1	76.3	64.1	56	74.6
	Minimum (°F)		32.0	36.8	44.6	52.4	61.4	69.0	73.1	71.9	65.0	54.3	43.0	34.8	53.2
	Precipitation (in.)		1.94	2.55	2.82	3.30	5.41	3.29	2.53	2.26	3.35	4.81	2.87	2.66	37.79
	Degree Days	Heating	693	485	291	105	19	0	0	0	10	82	356	609	2650
		Cooling	1	10	9	57	222	423	576	550	328	91	12	1	2280

Monthly Precipitation													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
2001	2.83	8.17	4.15	2.03	6.03	2.15	0.04	6.14	1.42	4.84	0.85	2.14	40.79
2000	2.2	1.6	2.9	4.67	2.28	4.87	0.23	0	0.33	8.53	7.41	3.68	38.7
1999	3.01	0.42	1.91	2.88	8.16	2.05	0.99	0.44	2.05	2.79	0.29	2.68	28.07
1998	3.22	3.89	5.15	1.21	2.29	2.57	0	0.88	1.83	6.73	3.26	4.13	35.16
1997	0.52	8.54	2.25	5.46	3.68	3.98	1.09	2.57	0.85	4.87	1.58	5.07	40.46
1996	1.71	0.04	1.82	1.97	0.53	2.29	3.43	6.34	2.51	3.06	12.13	0.42	36.25
1995	2.02	0.75	5.4	4.84	8.35	2.39	2.39	2.26	3.44	0.94	0.83	1.68	35.29
1994	1.45	1.56	0.97	2.76	8.33	3.22	13.58	2.76	2.53	8.66	7.36	2.22	55.4
1993	1.63	6.86	2.22	4.04	2.58	2.82	0	1.71	8.09	5.2	1.61	3.18	39.94
1992	2.89	2.47	1.78	1.65	6.19	4.26	1.76	1.05	3.71	0.7	2.37	5.48	34.31
1991	2.02	1.16	0.82	3.57	4.75	2.57	2.95	5.39	4.23	10.05	2.04	7.37	46.92

Table 4.2 Continued.

1990	4.52	3.21	6.52	7.44	5.25	1.54	2.62	3.91	0.48	1.48	4.38	1.78	43.13
1989	4.23	3.66	4.09	0.77	5.31	8.28	2.68	0.72	4.55	1.76	0.45	0.36	36.86
1988	0.82	0.87	2.09	2.24	1.23	5.57	2.52	0.16	6.11	1.19	2.44	3.79	29.03
1987	2.08	3.55	2.9	0.02	10.23	3.67	1.75	1.55	4.59	0.86	4.59	4.94	40.73
1986	0	8.67	1.24	5.75	7.47	4.48	0	2.94	7.7	2.63	2.94	1.55	45.37
1985	1.11	0.8	3.73	5.63	3.67	4.21	2.97	0.3	4.22	4.49	1.38	0.67	33.18
1984	1.18	2.35	3.33	0.89	2.65	1.4	0.67	4.85	0.16	4.88	2.21	5.5	30.07
1983	1.68	0.95	2.67	0.49	5.05	1.18	2	2.19	0.09	9.63	2.89	0.55	29.37
1982	3.71	2.52	1.34	2.16	20.92	4.72	3.13	0.65	0.25	1.72	3.54	3.52	48.18
1981	0.53	1.66	2.97	3.12	8.74	3.27	4.25	1.2	5.51	23.46	2.04	0.14	56.89
1980	1.92	1.77	1.46	1.33	3.34	2.21	0.17	0.28	8.14	3.79	1.34	1.97	27.72
1979	2.54	3.02	5.59	3.21	5.64	1.18	1.73	3.49	1.32	2.85	0.33	2.74	33.64
1978	2.27	3.08	2.55	3.63	5.83	0.97	1.87	1.89	1.33	0.13	3.74	0.13	27.42

*Data acquired through the National Weather Service, 2001

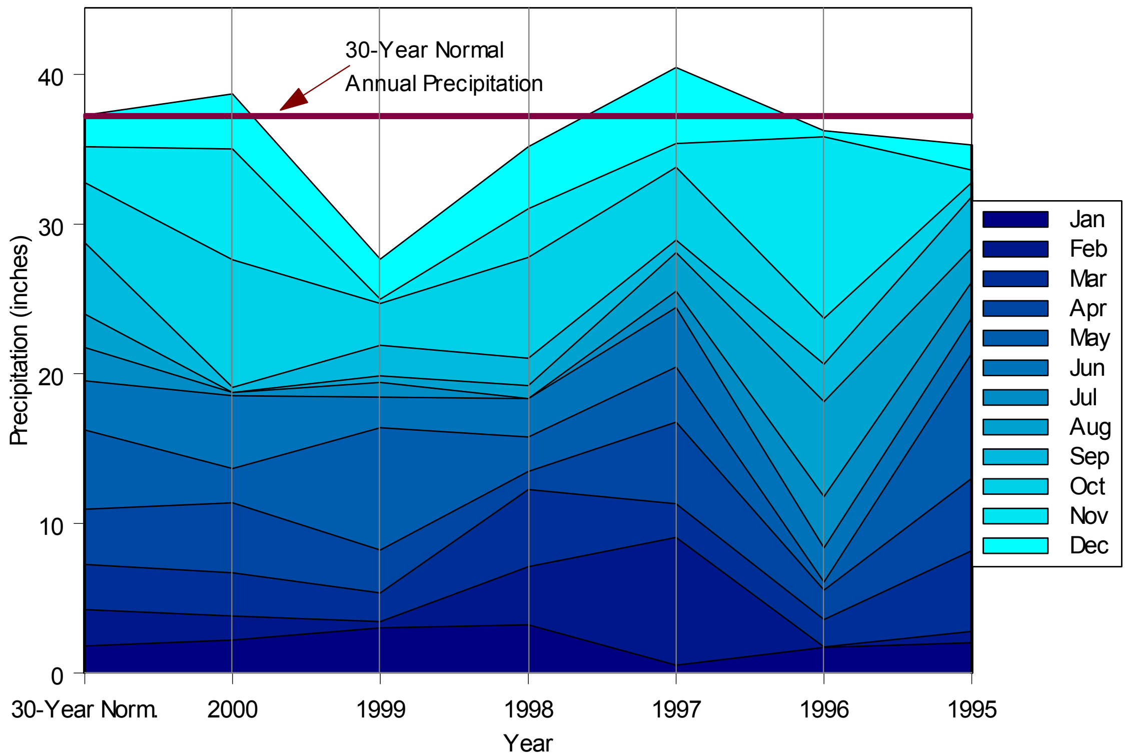

Figure 4.1 Monthly and annual precipitation totals for Denton, Texas with 30-Year Normal precipitation.

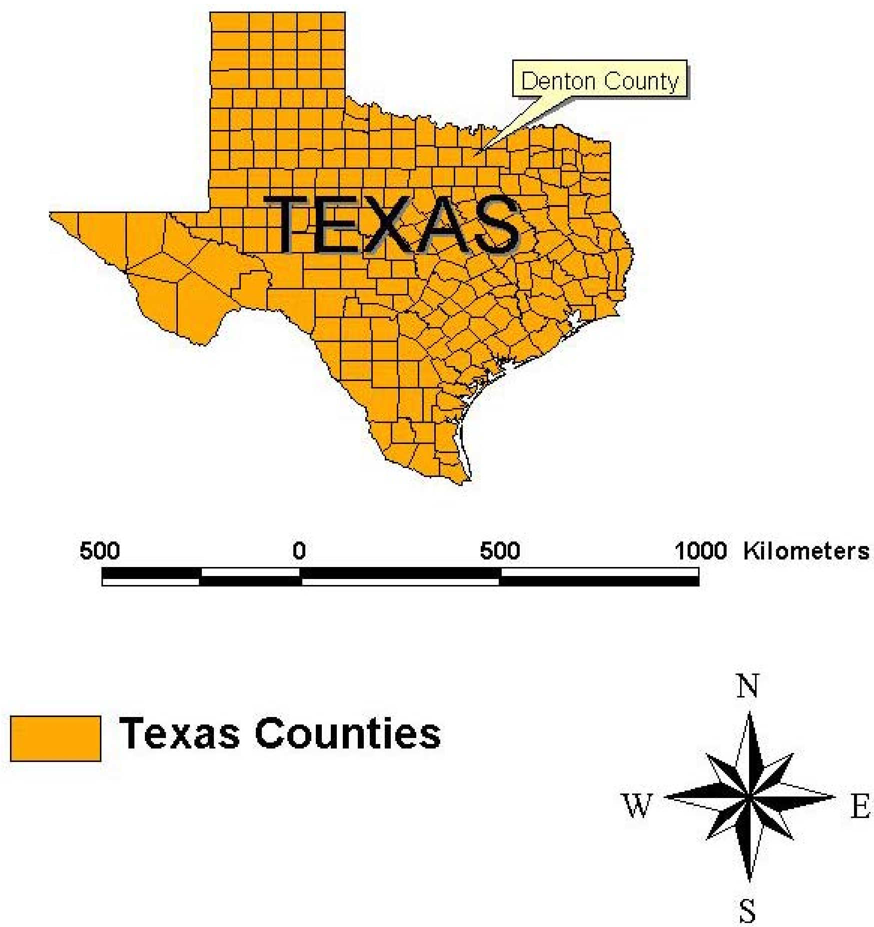

Figure 4.2 Location of Denton County in North Central Texas.

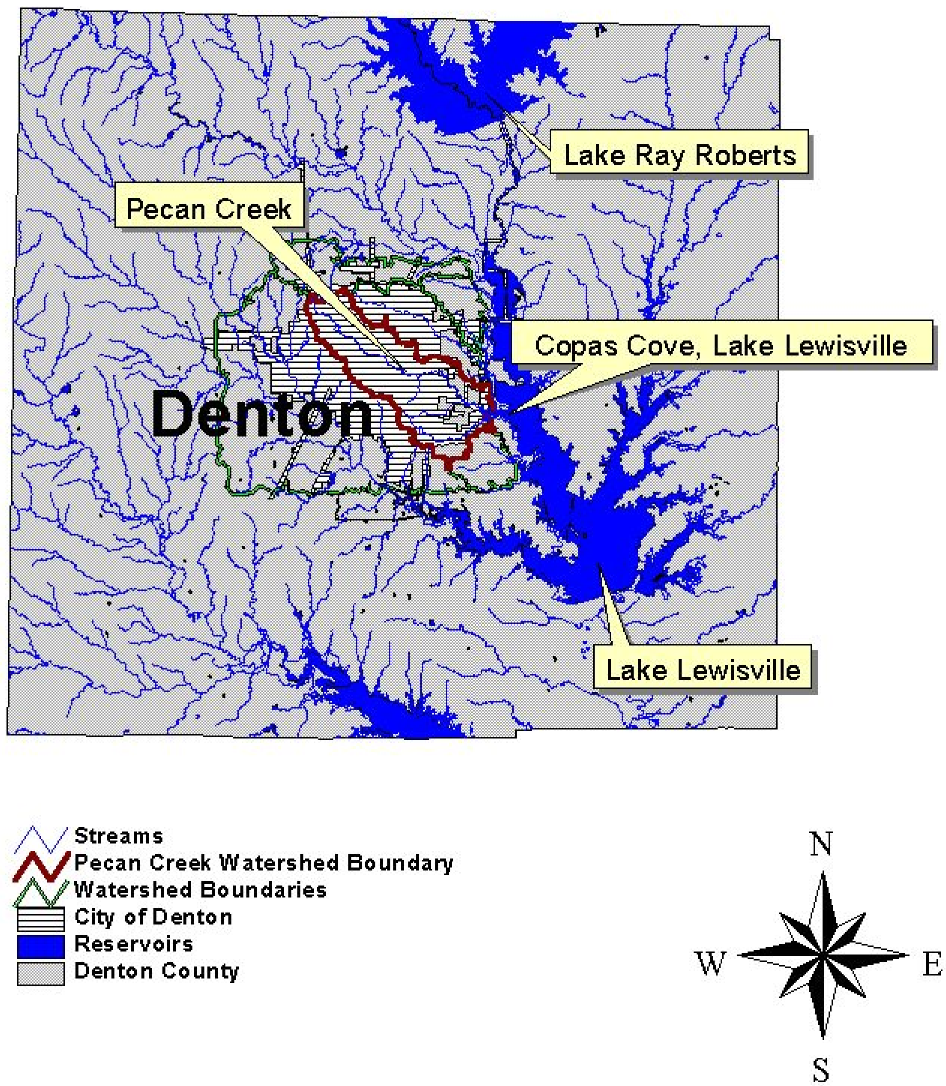

Figure 4.3 Location of Pecan Creek watershed in Denton County, Texas.

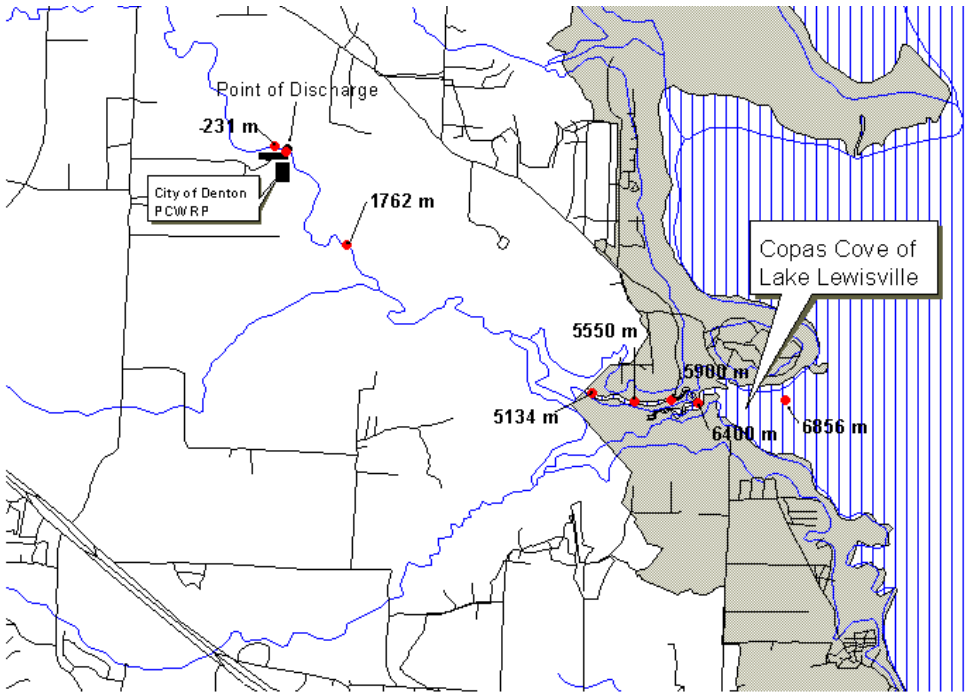

Figure 4.4 Pecan Creek monitoring stations.

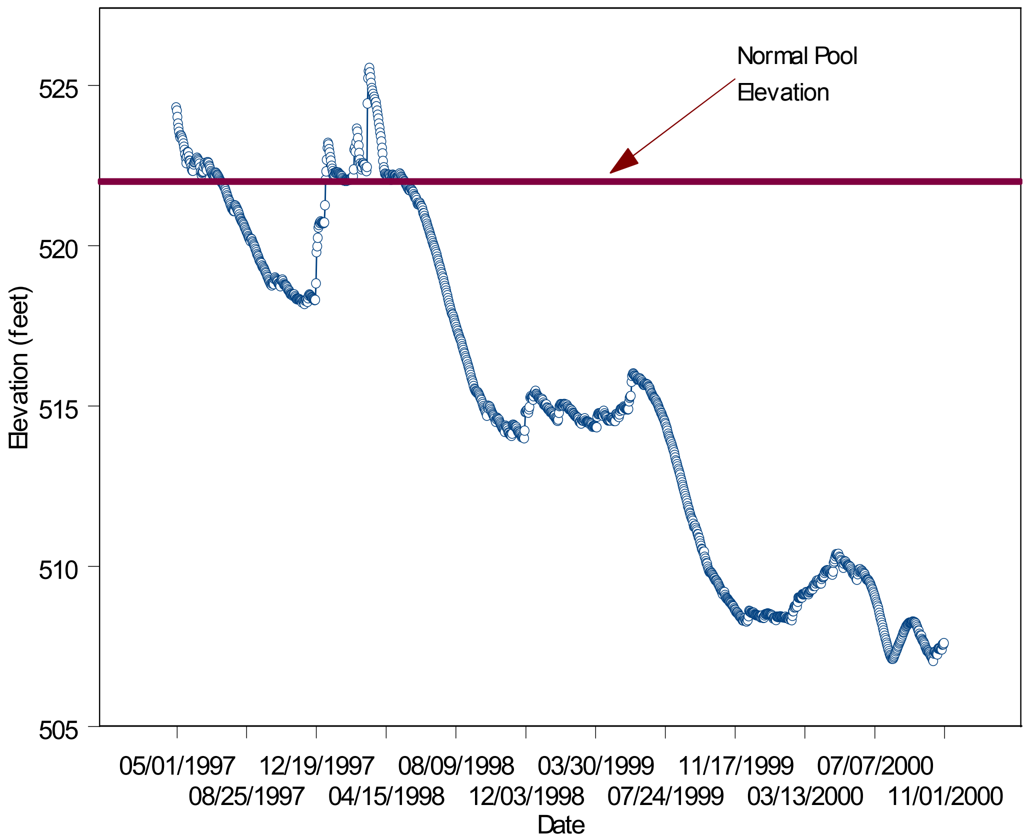

Figure 4.5 Lake Lewisville pool elevations during the period from May 1997 through October 2000. A reference line at 522 feet indicates normal pool elevation.

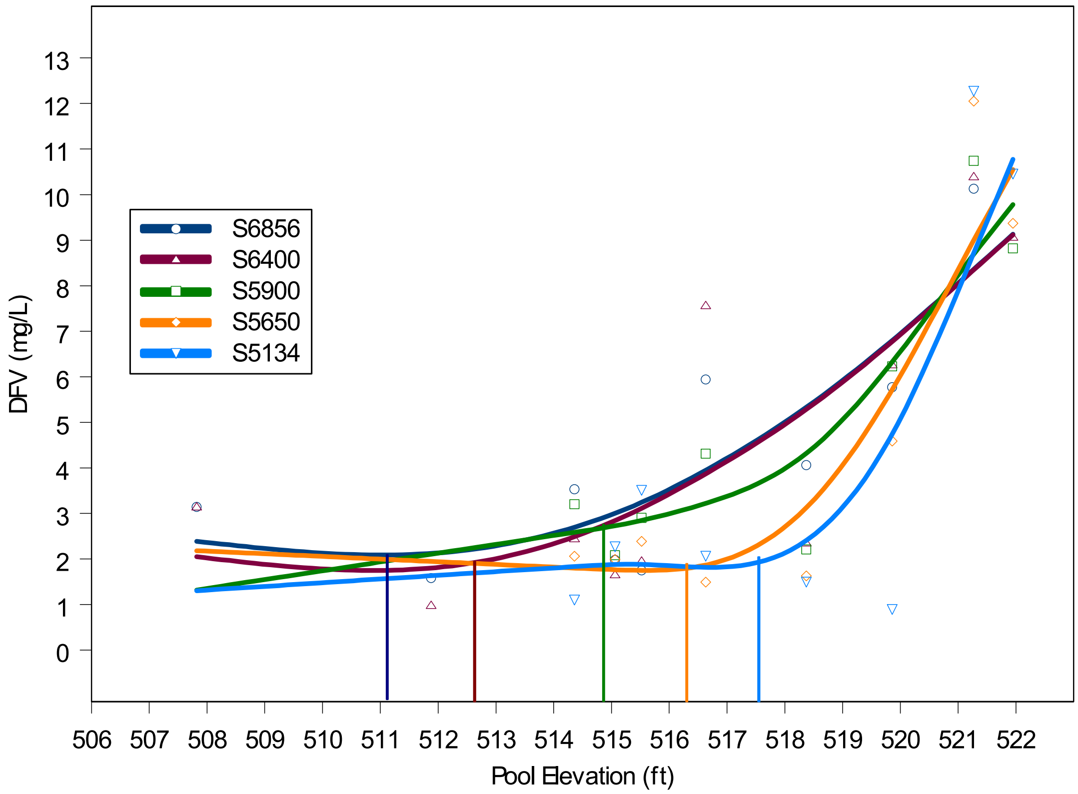

Figure 4.6 Spline plots of the DFV (Diurnal Fluctuation Value) response to Lake Lewisville pool elevation (ft). Points of change to lotic conditions are indicated on the graph by the vertical lines for each site. Corresponding elevations are: +5,134 = 517.6, +5,650 = 515.3, +5,900 = 514.9, +6,400 = 512.6, and +6,856 = 511.1.

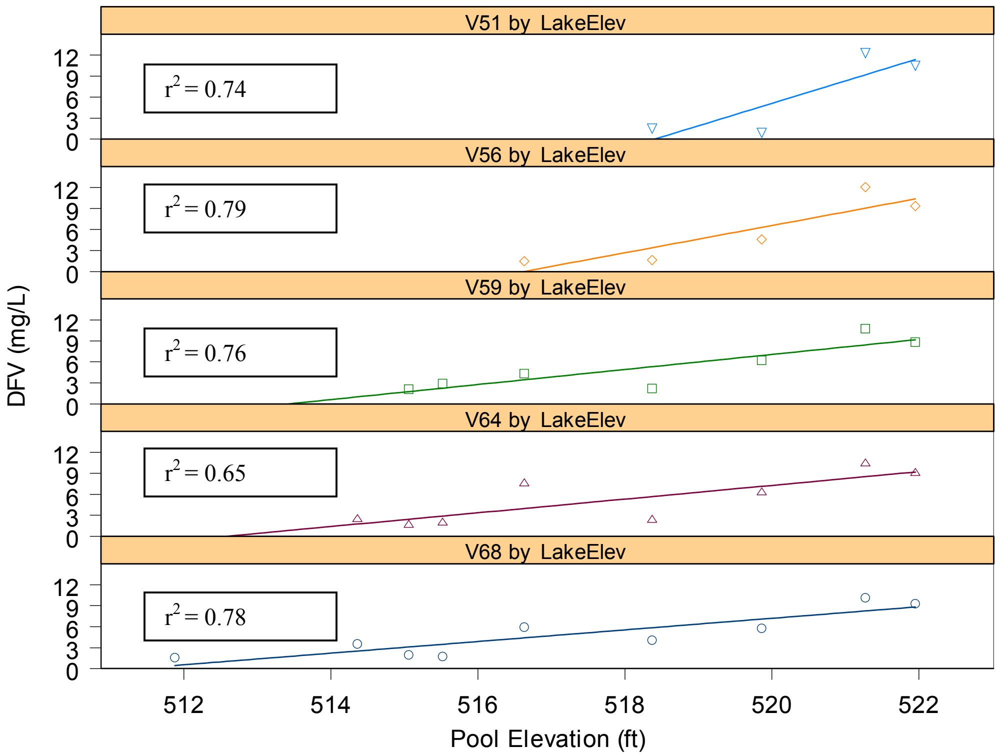

Figure 4.7 Regression analysis of Lake Lewisville Pool Elevation (ft) vs. DFV for Pecan Creek monitoring sites at +6,856 m, +6,4,00 m, +5,900 m, +5,650 m, and +5,134 m downstream of the PCWRP effluent discharge. Data represent DFVs during lentic conditions at each site. (v51 = +5,134 m, v56 = +5,650 m, v59 = +5,900 m, v64 = +6,400 m, v68 = +6,856 m)

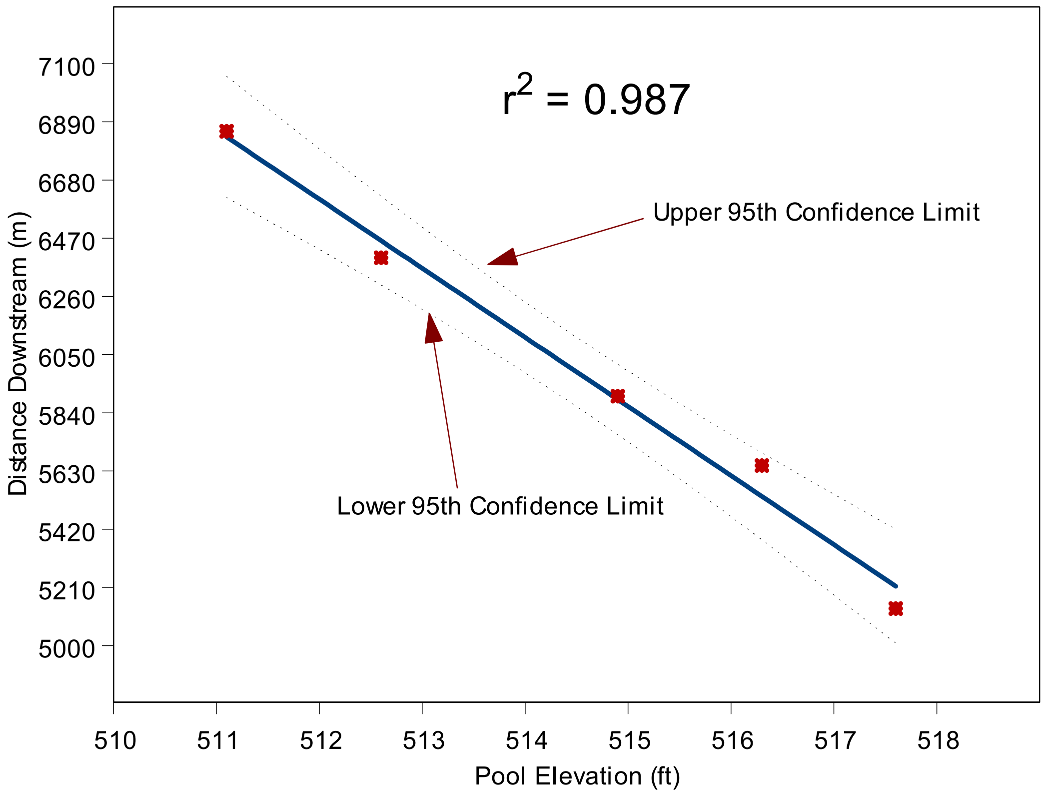

Figure 4.8 Determination of the critical distance for DO standard attainment. Regression analysis of Lake Lewisville pool elevation (ft) versus upstream extent of lentic conditions as distance downstream from the PCWRP effluent discharge.

CHAPTER 5

DETECTION OF WATER QUALITY CHANGES IN A RESERVOIR BACKWATER AS INFLUENCED BY STORM EVENTS AND URBAN RUNOFF

Introduction

Urbanization of a watershed can impose a multitude of impacts on downstream surface water quality (Booth and Jackson 1997). Impacts from urbanization can influence both the form and function of aquatic systems and can result in increased loadings of nutrients and other pollutants. Runoff pollution can degrade water quality, instream uses, and increase the risk of contamination to drinking water supplies (Appel and Hudak 2001).

Under the current National Pollutant Discharge Elimination System (NPDES), Phase 2, stormwater is required to be monitored to assess pollutant loads. This requirement now applies to municipalities with separate storm sewer systems that serve less than 100,000 people. Although the NPDES system requires direct measurement of pollutant loads during storm events there is not a clear link to the measurement of impacts that occur further from the source. This is especially true if the receiving stream is intermittent and the final receiving waterbody is a reservoir backwater.

In an effort to characterize the impact of wet weather events (storm events) and urban runoff on downstream reservoir conditions a water quality-monitoring program was initiated. This paper describes a case study of a low-flow intermittent stream, Pecan Creek, which receives effluent from a municipal Water Reclamation Plant (WRP) and stormwater runoff from the City of Denton in North Central Texas, which eventually discharges to a multi-purpose reservoir, Lake Lewisville. Monitoring was undertaken to characterize water quality trends in the reservoir backwater resulting from base flow loadings and stormwater runoff during low-flow summer conditions, and to assess the detection of stormwater events by the indirect measurement of water quality in the reservoir backwater. Study components enabled determinations of the magnitude of precipitation events necessary to cause changes in stable summer reservoir water quality conditions and measurement of the potential duration of such changes.

In meeting water quality standards NPDES permitting typically requires some type of water quality modeling (Thomann and Mueller 1987; Lung 1998). However, typical modeling is done for low flow stream conditions (USEPA 1991). If such modeling is based on monitoring data collected when downstream conditions are under the influence of previous storm events the NPDES permit conditions may reflect both the impact of point and nonpoint sources (Warwick and Roberts 1992). Under this circumstance the WRP or point source discharge would be held accountable for pollutant loadings for which they have no control. This case study shows that stream water quality may return to pre-storm conditions while backwater water quality may be changed for a period of days to weeks.

In an attempt to elucidate water quality conditions impaired by storm events in the downstream backwater areas of Pecan Creek nonparametric statistics were applied to analyze water quality and precipitation data (Gabriel 1971; Everitt 1980; Johnson and Wichern 1982; Sokal and Rohlf 1998). It was hypothesized that storm events occurring during stable summer conditions would result in significant changes in receiving reservoir water quality that could be statistically detected.

Given the potential impact of nonpoint and point sources, methods to assign proper loadings for NPDES compliance and protection of water resources are critical (Lung 1998; USEPA 1999). The assessment of water quality changes, both in receiving streams and in downstream reservoirs, is necessary to determine critical conditions and required to determine wasteload allocations and total maximum daily loads. A problem with assessing pollutant loads and modeling streams that discharge to reservoirs, especially intermittent streams, is how to determine when representative critical conditions occur in downstream receiving zones that are not impacted by storm events or other circumstances. Methods are needed to accurately group events based on observed data, in this case events that show stormwater impacts, indicate stable summer conditions, or represent extended periods of no rainfall. Since low-flow streams can be effluent dominated, dry summer conditions may be the most limiting for determining NPDES point source compliance. However, stormwater runoff can alter downstream water quality conditions in backwaters of streams for extended periods of time. This paper illustrates the importance of monitoring water quality conditions of reservoirs that receive low-flow to intermittent urban streams and the implications for determining critical conditions for water quality modeling and NPDES compliance. Likewise, it provides a method whereby stormwater and water quality managers can assess the duration of impacts and elucidate trends in water quality data. Lastly, it provides an approach that combines water quality monitoring and statistical analyses to augment water quality modeling as a tool for water quality and stormwater management.

Methods

Study Area

The City of Denton is located in Denton County of North Central Texas (Figure 5.1). During the past decade Denton has experienced rapid urbanization and population growth. In 2000 the City of Denton began upgrades to their 15 MGD WRP to increase the service area and prepare for continued population growth. Upgrades to the facility will constitute a change in design effluent flow to the receiving stream, Pecan Creek, with a maximum of 21 MGD.

Pecan Creek is an intermittent stream that flows through the City of Denton. The Pecan Creek watershed drains 63.5 km^2 and includes much of the most urbanized area of Denton. A 3^{rd} order stream, Pecan Creek receives effluent discharges from two point sources, nonpoint source runoff from the City of Denton Texas, and eventually flows into Lake Lewisville (Figure 5.2). Lake Lewisville is a multi-purpose reservoir and is the source water for the City of Denton's drinking water.

Water Quality Monitoring

Water quality monitoring of the receiving cove of Lake Lewisville (Copas Cove) was conducted in 1997 to develop a database of water quality conditions to assess the influence of base flow loadings and storm events. Monitoring provided data that could be used as a benchmark to assess future conditions.

Water quality monitoring was also performed to determine the area of the stream and reservoir backwater most impacted by point source discharges from the City of Denton's WRP. Results showed that the dissolved oxygen sag was typically detected at or about 5,134 m downstream. In an effort to characterize downstream water quality trends this station and others were monitored. However, the purpose of this paper was: 1) to assess the impact of stormwater on reservoir backwater water quality at 5,134 m downstream from the effluent discharge; 2) determine if reservoir backwater conditions under the influence of storm events were statistically different from stable summer conditions; and, 3) develop a method to determine when backwater water quality was representative of point source impacts. Information to determine the period of stormwater influence on backwater water quality was necessary to accurately model water quality to establish future permitted loads for the WRP.

Water quality measurements of dissolved oxygen (mg/L), temperature (ºC), specific conductance (µs/cm), and pH (s.u.) were made at each location with a Hydrolab® Datasonde and Suveryor 4, water quality meter. Water quality parameters were assessed throughout the water column at 0.5 m increments and near the surface of the water column.

Sampling was relegated to summer months, as the initial purpose of the study was to assess the impact of the City of Denton Wastewater Treatment Plant effluent on low-flow stream conditions during the summer. One sampling event, September 3, 1997 was conducted immediately prior to and following a significant rain event to assess the influence of stormwater runoff in the area of the backwater. All other events preceded and followed storm events by a range of 6 to 28 days. A primary objective of the study was to assess the water quality trends as influenced by storm events and base flow loadings of chemical and water quality constituents. It was anticipated that storm events would have the greatest impact on receiving reservoir water quality during periods of minimal base flow, summer low-flow conditions.

In consideration of point source loadings, base flow was typically found to be about 90% effluent flow during most summer months, except during periods when the stream went dry. Relatively constant effluent loadings provided an opportunity to measure changes in steady state water quality conditions as influenced by the occurrence of storm events. Likewise, study components were designed to assess future water quality monitoring needs for the City of Denton and the displacement of pollutant loads in the downstream reservoir.

Statistical Analyses

Data sets used in these analyses were: 1) a data set containing water quality data for the backwater monitoring site composed of 4 water quality variables; 2) a data set containing water chemistry composed of 10 variables; and, 3) a data set containing rainfall data, values for Days Since Precipitation (DSP). Values for DSP were simply the number of days of no precipitation preceding a water quality-monitoring event.

Statistical analyses of water quality data were accomplished with the use of the S-Plus statistical computer package (MathSoft 1999; MathSoft, Inc. 2000). An initial preliminary statistical assessment was completed for each data set by exploratory data analysis. Preliminary assessments of changes in water quality and diurnal trends were performed with a suite of summary statistics and graphs. However, it was determined that comparing the median, maximum or minimum values was not sufficient to detect long-term changes and differentiate storm influences from stable pre-storm conditions. Therefore, the diurnal fluctuations were compared and input into the data matrix. The diurnal fluctuation for a monitoring event was calculated as the maximum minus the minimum value for each water quality parameter. These values indicated the magnitude of change during an approximate 24-hour period. Comparatively, these changes could not be represented accurately using a median, maximum, or minimum value.

To determine the impact of storm events on water quality the measurements were organized in a data matrix. Variables were grouped by measurement date. The matrix consisted of values for the range of diurnal fluctuations observed in water quality variables, taken as the maximum value minus minimum value measured for a monitoring period, and DSP values. A matrix was used to develop data sets that were both acceptable for use in a subroutine within S-Plus for cluster analysis and Principal Components Analysis (PCA). These nonparametric methods were chosen, as they did not restrain the analyses based on assumptions of normality required for parametric tests. Likewise, these methods were robust enough to allow patterns in the physical-chemical data set to be examined. The intent of statistical analyses was to determine the parameters that were most influenced by storm events, assess the trend in storm event impacts, evaluate the duration of change, and determine a method to accurately group events based on observed data. This information is critical to management of the Pecan Creek system as future storm loadings can be assessed by direct water quality measurement and long-term trends in reservoir water quality can be compared during periods of low stream flow. Water management strategies such as these are needed universally.

Results

Data were analyzed independently by date, as water quality conditions were found to vary and the response was time-dependant. The typical pattern during the summer months of 1997 was to have extended periods of dry weather followed by the occurrence of significant isolated storm events. Following storm events there would be a surge in flow followed by the stream quickly returning to near pre-storm base flow conditions, on the order of one to two days, and stabilizing. Storm events for the study period were monitored by the measurement of significant precipitation events at the Lake Lewisville Dam (Figure 5.1). For this study, we define significant as a storm event that produced 0.5 inches of precipitation or more in a 24-hour period or less. Monthly precipitation totals for the City of Denton were also assessed for the monitoring period. These data were readily available from the National Weather Service (National Weather Service, Ft. Worth/Dallas 2001).

Storm Events

Precipitation data collected at Lake Lewisville Dam was acquired from the U.S. Army Corps of Engineers, Fort Worth District. Rainfall data were daily 24-hour totals collected at 8:00 a.m. each day. Storm events for the period of July through September 1997 are summarized in Figure 5.3. In 1997 three major rain events were recorded at Lake Lewisville Dam. These events ranged in intensity and duration, with each proceeding storm increasing in the total amount of precipitation. These data show the typical pattern of summer rain events, extended periods of dry weather with intense storm events over an approximate 24-hour period. During 1997 some events included the measurement of precipitation over a period greater than 24-hours. Each of the three major storm periods had total rainfall in excess of 0.5 inches.

Water Quality

Water quality monitoring in 1997 was conducted during a period that Lake Lewisville was at or near full pool conditions. These conditions were deemed to represent the greatest impacts from the City of Denton WRP on Pecan Creek water quality. An intensified sampling strategy was applied on an approximate weekly basis in 1997 to determine the variability of water quality constituents and to collect background data to support future water quality studies. It was determined during routine sampling that storm events influenced the diurnal fluctuations of water quality data and altered the flow regime of Pecan Creek. Water quality in the lotic zones of Pecan Creek was found to return to stable conditions between monitoring events and in the backwater areas the change was more long-term.

Water quality data for a site 5,134 m downstream from the WRP discharge continuously showed the greatest impact from the WRP. At this location the stream became a backwater area due to damming by the waters of Lake Lewisville. Therefore, the load of oxygen demanding wastes in the effluent stream and in the runoff from the City of Denton had the greatest impact at this site, causing a sag in dissolved oxygen levels.

Detection of Water Quality Changes

Detection of water quality changes was accomplished by applying nonparametric statistics. Data were analyzed by use of cluster analysis and PCA. By grouping data by date the influence of storm events was investigated. Cluster analysis results showed that water quality data could be grouped based on dissolved oxygen diurnal fluctuation and DSP values (Figure 5.4). Cluster analysis results show that groupings occurred that were indicative of stormwater impacts. Data could generally be grouped into three categories based on days since a storm event due to changes in water quality. Based on the DSP values data could be grouped as values of 7 or less, 8 to 20, and 21 or greater. Pre-storm water quality conditions were indicated to reestablish beyond 7 days, as witnessed by water quality monitoring. In this study, storm events broke down the stratified conditions of the backwater area, reduced DO values, and condensed the range of diurnal fluctuation in DO.

PCA was further used to group the data and determine the parameters that explained the majority of the variability. Results for the PCA biplot substantiated the groupings derived from the cluster analysis (Figure 5.5). The loadings of the variances are shown in Figure 5.6. Component 1 of the PCA explained 0.655 of the variance (total = 1) and Component 1 and 2 explained 0.992 of the variance. Variance of Component 1 was comprised primarily of dissolved oxygen and DSP, whereas Component 2 was primarily DSP and dissolved oxygen (Figure 5.7).

Discussion

Pecan Creek is an intermittent stream that receives point source loadings from a WRP and nonpoint source loadings from urban landuses. Water quality and precipitation data were assessed to address the impact of stormwater runoff on water quality conditions of the backwaters of Pecan Creek. Data were also used to clarify when the backwater area was under the influence of the WRP discharge as compared to periods when there was also a stormwater impact. Results of the study indicated that the influence of storm events could be detected by water quality monitoring data up to 7 days after a storm event. Monitoring data collected within 7 days of an event was differentiated from those occurred from 12 to 27 days after a storm event, according to the statistical analyses. Further division of the monitoring events based on water quality and DSP, as evidenced from cluster and PCA analyses, showed that events could be grouped in categories of ≤ 7 days, 12 to 19 days, and ≥ 21 to 27 days after a storm event. Results indicated that diurnal fluctuations in dissolved oxygen, temperature, and pH were impacted by storm events. Thus, when combined with DSP, the monitoring events could be separated into those showing stormwater impacts, events that were characterized by stabilization of stratified conditions, and long-term stabilization of reservoir water quality conditions.

Implications of these results for the backwater area of Pecan Creek are that while stream conditions may not exhibit stormwater impacts, the backwater areas of Pecan Creek may exhibit stormwater impacts for extended periods, measured in days. These data suggest that monitoring in the backwater areas is essential to understanding the consequences of increases in impervious cover and urban landuses in the basin. Throughout the study period monitoring events that occurred within 7 days of a storm event showed reduced dissolved oxygen and reduced diurnal fluctuations in dissolved oxygen concentrations. This could be expected as storm events in the watershed have been shown to increase loadings of biochemical oxygen demanding compounds (Appel and Hudak 2001).

Implications of this study for environmental management in the Pecan Creek basin are: 1) monitoring of the backwater areas should continue to assess the landuse changes in the watershed on water quality conditions, 2) a goal of environmental management should be to minimize stormwater impacts on backwater dissolved oxygen that result in reduced concentrations, 3) backwater water quality is probably the best indicator of the efficiency and sustainability of best management practices to reduce stormwater flows in Denton, and 4) backwater quality shows an extended change in water quality as a result of storm events. Likewise, when addressing the impacts of point source loadings in Pecan Creek, care should be taken to differentiate periods that are under the influence of stormwater loadings. By monitoring water quality within a short duration after a storm event (≤ 7 days) in backwater areas, inaccurate conclusions concerning point source loadings could be made. Water quality conditions under the influence of storm events may show a greater reduction in DO levels.

These findings represent an important step to understanding the implications on monitoring and modeling the water quality in backwater areas of streams that discharge into reservoirs, especially in the semi-arid portions of Texas. Results show that water quality data collected within a week of storms should not be used to accurately model the impacts of point source loadings. Although, this timeframe may not hold for other streams throughout Texas the results show that care should be taken to distinguish data sets that are under the influence of stormwater conditions.

Future recommendations for monitoring would be to collect more accurate rainfall and stream flow data in the basin and determine the magnitude of storm events that result in detected changes in water quality in the backwater area. The reduction of stormwater flows and treatment of stormwater may results in a reduced duration of impacts. However, a more intensified sampling strategy will be needed to detect these changes. Lastly, water quality managers that depend on water quality measurements to address loadings should examine wasteload allocations based on monitoring events in backwater areas and adjust modeling to only point source impacted monitoring events.

Conclusions

Pecan Creek is impacted by urban runoff and receives an effluent discharge from the City of Denton’s WRP. In conducting a study to assess the impact of the WRP discharge on the water quality conditions of the backwater areas of Pecan Creek, which interface with Lake Lewisville, the influence of storm events were assessed. Water quality data were collected both before and after storm events to meet the following objectives:

1. Characterize the impact of wet weather events (storm events) and urban runoff on downstream Pecan Creek backwater and reservoir conditions;
2. Provide a case study of a low-flow intermittent stream that receives a WRP effluent and stormwater runoff from an urban area;
3. Assess the detection of stormwater events by the indirect measurement of water quality in a reservoir backwater;
4. Determine the duration of stormwater impact to assess when monitoring for NPDES compliance should be performed; and,
5. Apply nonparametric statistics to elucidate water quality conditions under the influence of stormwater events as compared to stable base-flow conditions.

Water quality observations for the portion of Lake Lewisville receiving flows from Pecan Creek indicate that much is to be learned about the influence of WRP discharge and stormwater runoff on Pecan Creek and Lake Lewisville water quality. As the population in Denton increases and effluent loadings increase these dynamics may change. Future monitoring and assessments of Pecan Creek water quality will be needed to quantify these changes. In characterizing the impact of storm events, it was discovered that water quality may be influenced for a period of up to 7 days in the backwaters of

Pecan Creek/Lake Lewisville. As such, future monitoring to assess NPDES compliance for the WRP should be done only during periods that exhibit stable base-flow conditions. During this study, stable conditions exhibited increased diurnal fluctuations of DO, as measured over an approximate 24-hour period. Thus, the diurnal fluctuation of DO can be used as an indicator of the impact of storm event urban runoff on water quality.

In assessing the water quality of Pecan Creek some important conclusions can be made in regard to the WRP. The influence of the WRP nutrient loadings on phytoplankton and bacteria dynamics within Pecan Creek should be studied to determine best management practices for the facility. Observations showed that nutrient levels were reduced from the point of WRP discharge and downstream into Lake Lewisville. Additionally, increases in BOD_5, DO variability, and chlorophyll *a* in the backwater regions indicated that phytoplankton dynamics are influenced by the WRP discharge. As such, base-flow water quality dynamics change in conjunction with changes in the biological community. Therefore, during base-flow events Pecan Creek water quality is controlled by internal factors. During storm events external factors associated with stormwater runoff caused a detectable change in water quality. Future studies to quantify the bacteria and phytoplankton community and seasonal dynamics, as well as sediment oxygen demand, may shed light on ways to optimize the WRP effluent discharge under base-flow conditions.

Pecan Creek represents a common case across much of Texas, an intermittent urban stream receiving point source discharges and stormwater runoff. Future research of Pecan Creek will increase the ability of environmental managers, scientists, and regulators to deal with water quality challenges in these situations in North Texas and other parts of the country. Lastly, to promote a more holistic watershed management paradigm, nonpoint source contributions should be assessed as to temporal and spatial impacts on Pecan Creek water quality.

The water quality study conducted as part of this research illustrates the need for automated monitoring of stream flows in Pecan Creek to address the wasteload. As the WRP is upgraded these data will be necessary to elucidate the influence of the discharge as compared to nonpoint source pollutant loads from urban landuses in Denton. A continued focus should be made to determine the changes in the dissolved oxygen resources of the stream and to better understand the influence of storm events and droughts.

Lake Lewisville is an extremely important resource for North Central Texas. The reservoir serves as a drinking water source for the City of Denton, a recreational magnet for North Texas, and has the capacity to degrade wastes received from both point and nonpoint sources. To provide a more comprehensive protection plan for this resource, nutrient inputs into the system will need to be assessed in light of point and nonpoint sources. It is recommended that the City of Denton consider measures to better control nutrient inputs from the WRP and reduce the diurnal variability of dissolved oxygen in the receiving cove of Lake Lewisville during base flow conditions.

Future water quality monitoring and modeling of the basin should incorporate a greater spatial component to better understand landuse changes and corresponding changes in water quality. Without knowledge of basin changes, management of water resources will be difficult. Such a model should be developed on a sub-basin level to address best management practices that can be applied to change downstream water quality conditions.

Lastly, the use of nonparametric statistics, both cluster analysis and PCA, were used to elucidate changes in water quality as influenced by storm events. This case study showed that this method of combining multiple water quality parameters and DSP values was effective in grouping events that were influenced by storm events, represented stabilizing base-flow conditions, and that showed more long-term stratified summer conditions. The application of nonparametric statistics is a useful tool to separate water quality observations that are influenced by storm events. These techniques should be applied on a more regular basis by primacy agencies and stakeholders, in order to assure a more consistent method of assessing WRPs and NPDES permit conditions when performing water quality modeling.

With rapid urbanization of the Pecan Creek basin, and many other basins like it across the Country, stormwater is emerging as a great environmental challenge for Municipalities. Therefore, understanding the effects of stormwater in aquatic systems is a paramount objective. Combining the efforts of scientists, managers, and stakeholders will be a necessity to bring about protection of these aquatic resources.

References

1. Appel, P. L. and P.F. Hudak. 2001. "Automated Sampling of Stormwater Runoff in an Urban Watershed, North-Central Texas." *Journal of Environmental Science and Health* 36(6):897-907.

2. Booth, D. B. and C.R. Jackson. 1997. "Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation." *Journal of the American Water Resources Association* 33(5):1077-89.

3. Everitt, B. 1980. "Cluster Analysis." New York: Halstad.

4. Gabriel, K. R. 1971. "The Biplot Graphical Display of Matrices With Applications to Principal Components Analysis." *Biometrika* (58):453-67.

5. Johnson, R. A. and D. W. Wichern. 1982. "Applied Multivariate Statistical Analysis." Englewood Cliffs, New Jersey: Prentice-Hall.

6. Lung, W. S. 1998. "Trends in BOD/DO Modeling for Wasteload Allocations." *Journal of Environmental Engineering* (October):1004-7.

7. MathSoft. 1999. "S-PLUS 2000 Modern Statistics and Advanced Graphics." Pp. 638 in *Guide to Statistics, Vol I.* Seattle, WA: Data Analysis Products Division, MathSoft, Inc.

8. National Weather Service, Ft. Worth/Dallas. 2001. "Normal, Means, and Extremes" [Web Page]. Accessed 21 Nov 2001. Available at http://www.srh.noaa.gov/fwd/CLIMO/coop/denton.html.

9. Sokal, R. R. and F. J. Rohlf. 1998. "Biometry: The Principles and Practice of Statistics in Biological Research." . third ed. New York: W. H. Freeman and Company.

10. Thomann, R. V. and J. A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. New York, New York: HarperCollinsPublishers Inc. 644 pp.

11. USEPA. 1999. "Guidance for Water Quality-Based Decisions: The TMDL Process" [Web Page]. Accessed 31 Mar 1999. Available at http://www.epa.gov/OWOW/tmdl/decisions.

12. ———. 1991. "Technical Support Document For Water Quality-Based Toxics Control." Pp. 145 in , vol. EPA/505/2-90-001Washington, D.C.: Office of Water.

13. Warwick, J. J. and L.A. Roberts. 1992. "Computing the Risks Associated With Wasteload Allocation Modeling." *Water Resources Bulletin* 28(5):903-15.

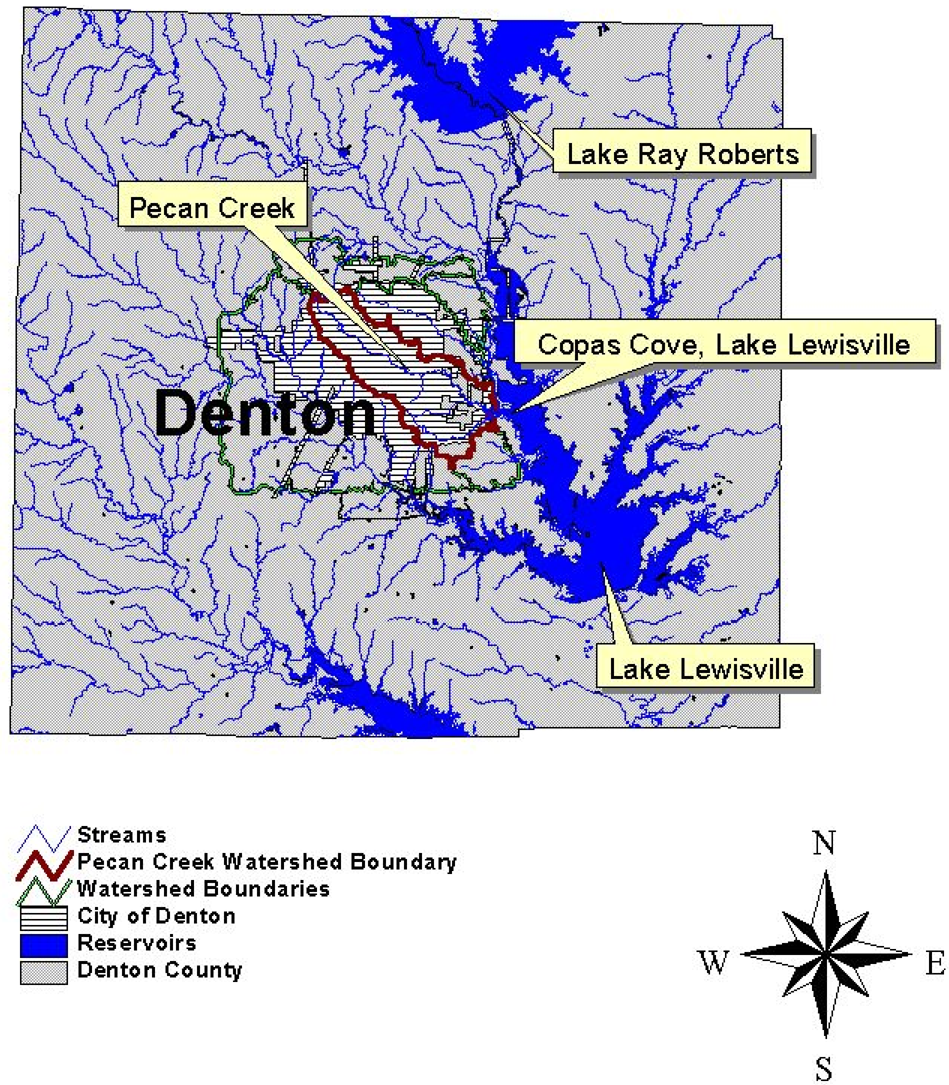

Figure 5.1 Location of the Pecan Creek study area in Denton County, Texas.

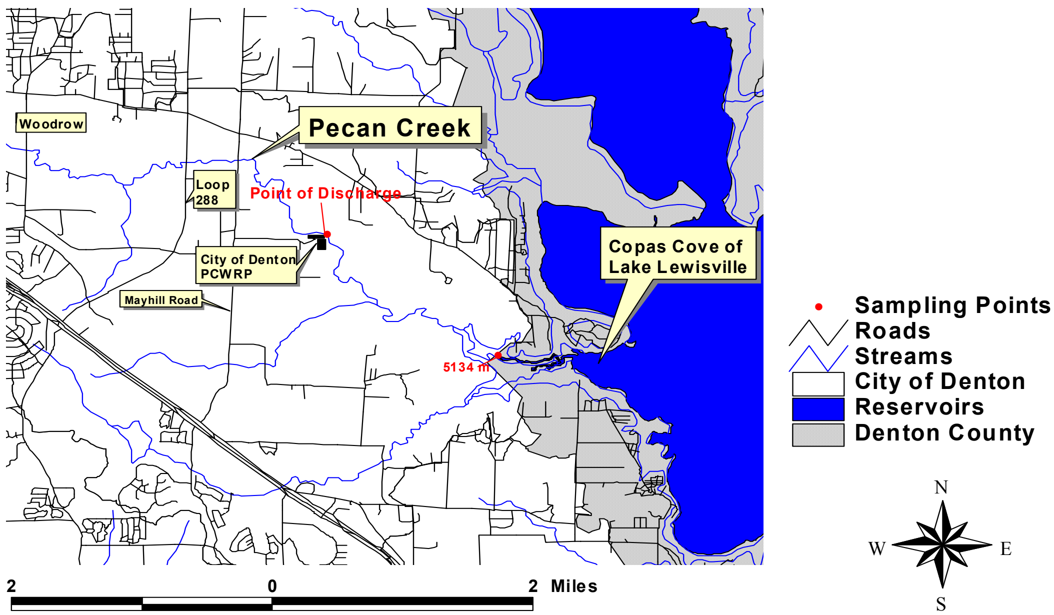

Figure 5.2 Receiving cove in Elm Fork arm of Lake Lewisville. Pecan Creek and Lake Lewisville water quality monitoring station at 5,134 m downstream from the WRP.

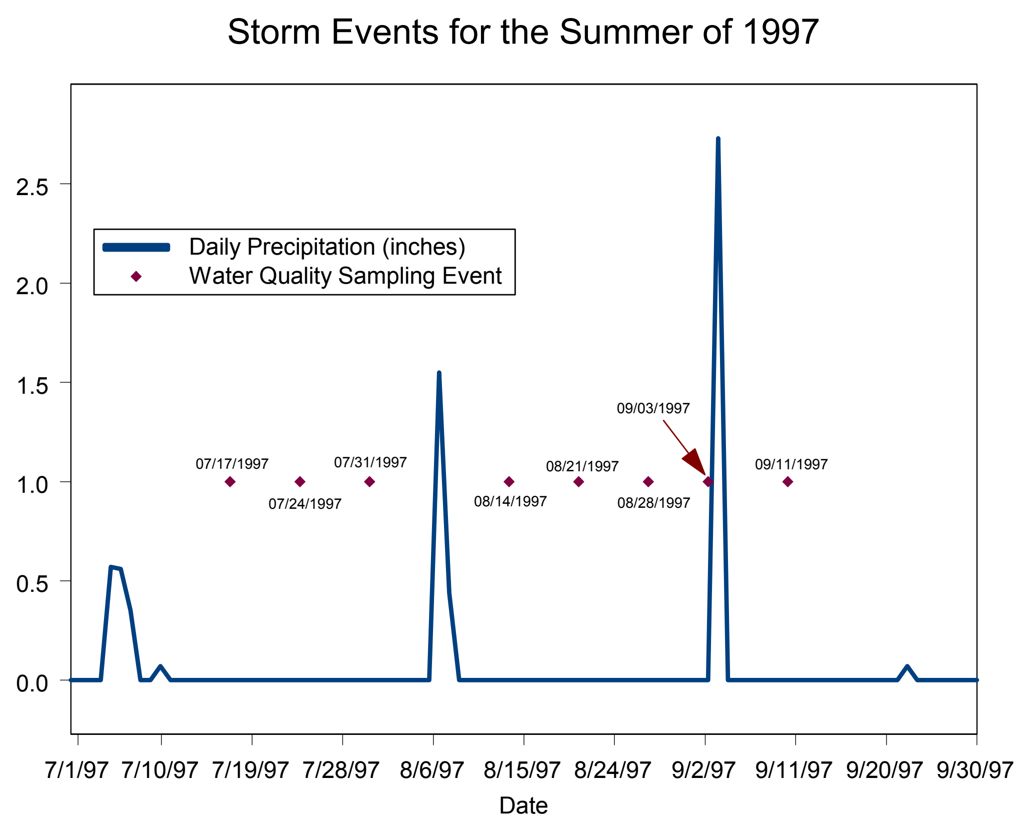

Figure 5.3 Precipitation measured in the summer of 1997 at the Lake Lewisville Dam, indicating storm water events.

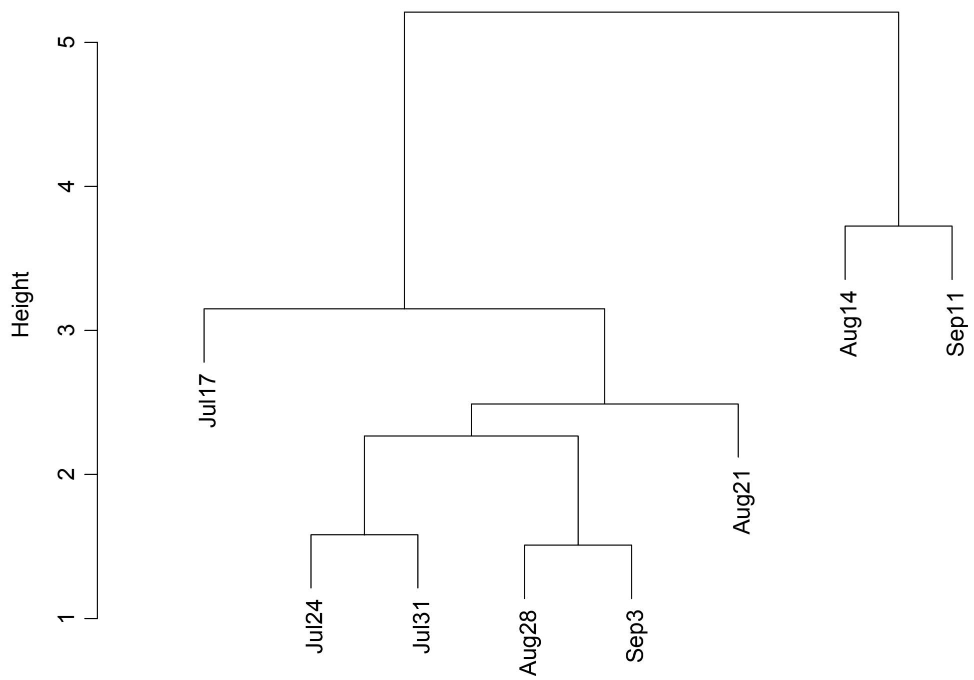

Figure 5.4 Cluster analysis results of water quality monitoring events for the backwater of Pecan Creek, 5,134 m downstream from the WRP discharge. Cluster analysis shows the separation of events following stormwater events. Events are grouped into three distinct categories, ≤ 7 days (September 11 and August 14), 12 to 19 days (July 17 and 24, and August 21), and 21 to 27 days (July 31, August 28, and September 3) following storm events based on dissolved oxygen, pH, and temperature 24-hour diurnal fluctuations, and DSP values.

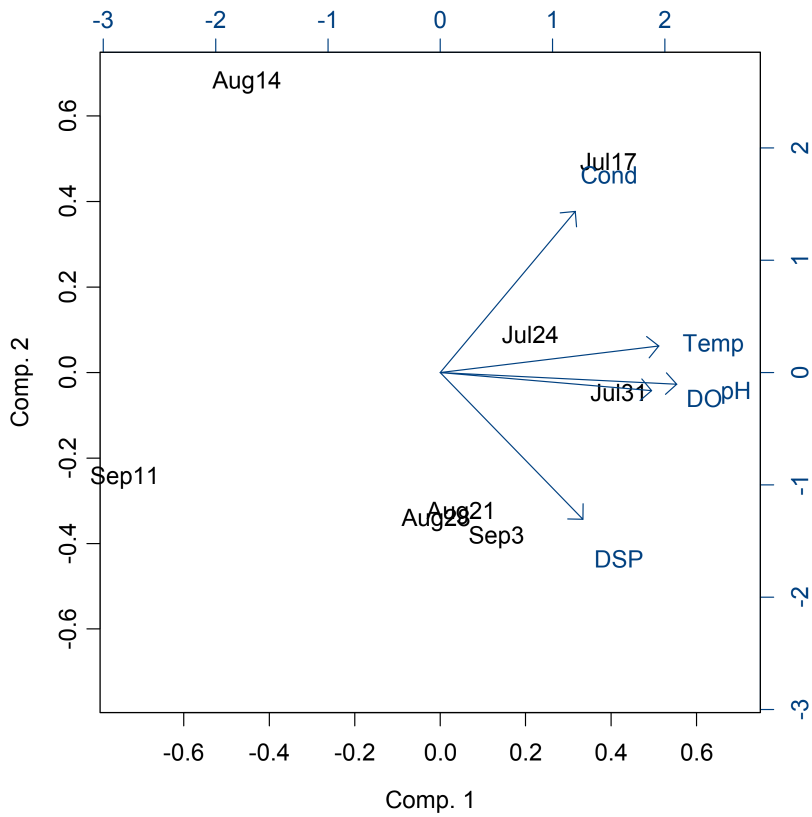

Figure 5.5 PCA biplot of the summer 1997 monitoring events. Groupings shown in the biplot are the same as those determined in the cluster analysis.

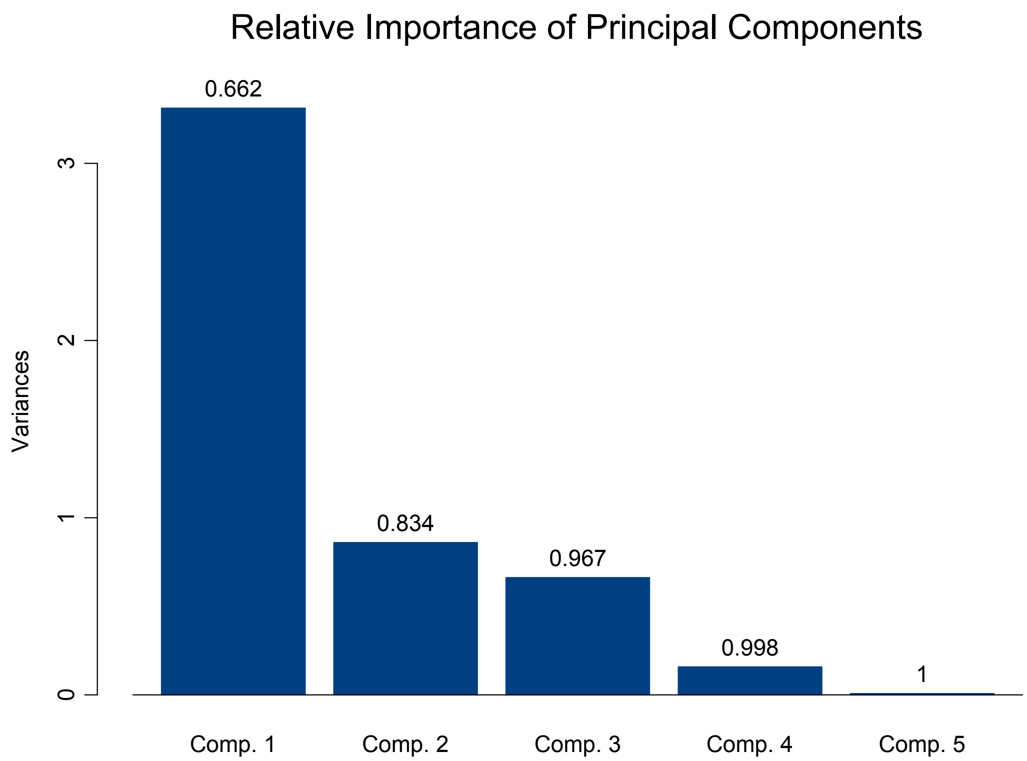

Figure 5.6 Loadings of the variance indicate the importance of the components of the PCA analysis. Principal component 1 and 2 explain a total of 0.992 of the entire variance (total = 1.0). These two primary components are sufficient to explain the differences between the monitoring events.

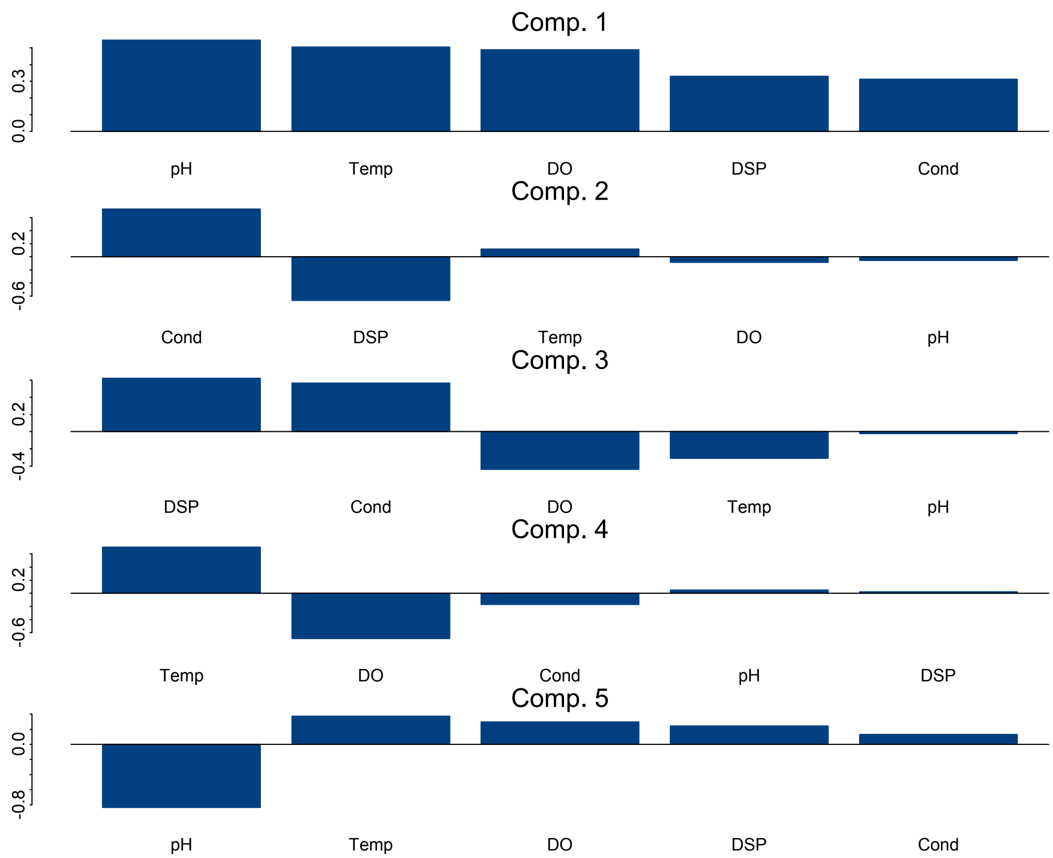

Figure 5.7 Screeplot of the PCA analysis showing the original variables that comprise each principal component. DSP and DO (dissolved oxygen diurnal fluctuation) are the primary original variables that explain the majority of the variance in the PCA model.

CHAPTER 6

FUTURE RESEARCH

Pecan Creek is a prime example of a stream that has been altered to suit the needs of a City. More or less, those needs have been to convey stormwater and wastewater from the City of Denton to Lake Lewisville. However, Pecan Creek is a viable aquatic resource that has the capacity to sustain aquatic life, degrade wasteloads from the City of Denton, and provide recreational opportunities for the citizens of North Central Texas.

Research conducted during this study has answered some questions and opened the door to more research opportunities in the basin. Particularly, there is a great need to understand the impact of storm events and urban runoff on the water quality and physical habitat of Pecan Creek. During this research a wasteload allocation was developed for the City of Denton WRP, the oxygen dynamics of the stream were explored, the influence of drought on the reservoir backwaters and effluent-receiving cove was investigated, and urban runoff impacts at the stream and backwater interface were detected. Further research within the Pecan Creek Watershed should be established to:

1. Determine the loadings of biochemical oxygen demand, nutrients, and other constituents from storm water events and urban runoff;
2. Develop a water quality model set based on observations of total nonpoint source loadings of pollutants in the basin, water quality in Pecan Creek, and point source loadings. This model could be used to develop a Total Maximum Daily Load (TMDL) for Pecan Creek.

3. Assess the physical habitat of Pecan Creek and begin to monitor the influence of runoff events on channel stability, sediment movement, and channelization.
4. Complete a landuse analysis that assesses the amount of impervious cover and the related loadings of pollutants in the basin;
5. Continue to monitor water quality conditions and changes in Pecan Creek, the reservoir backwaters, and in the receiving cove of Lake Lewisville. This monitoring program should guide future management decisions and activities.
6. Implement a monitoring program to observe the algae and bacteria dynamics in the backwater regions of Pecan Creek and determine the temporal and spatial dynamics in relation to dissolved oxygen.
7. Establish permanent water quality and storm event monitoring stations that have flow gaging capabilities. This will allow samples to be collected to assess nonpoint loadings and urban runoff events.
8. Continue a program of assessing climate and/or weather variables in relation to water quality in Pecan Creek and Lake Lewisville.

Future research will require the cooperation from the City of Denton, the University of North Texas, local citizens, and other stakeholders. The City of Denton has a unique opportunity to serve as an example for the rest of the nation: illustrating how a City and its citizens can be responsible for environmental stewardship. Likewise, the partnership that the City of Denton and the Environmental Science Program at the University of North Texas have established will be an integral relationship for the continued success of environmental programs.